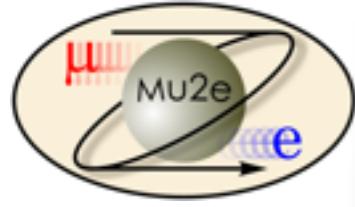


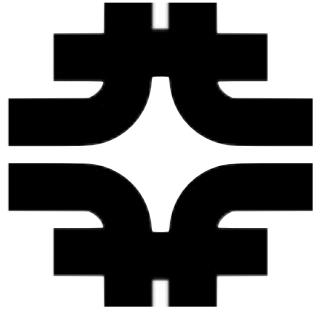
# The last oscillation: mu2e at Fermilab

Vadim Rusu  
Fermilab

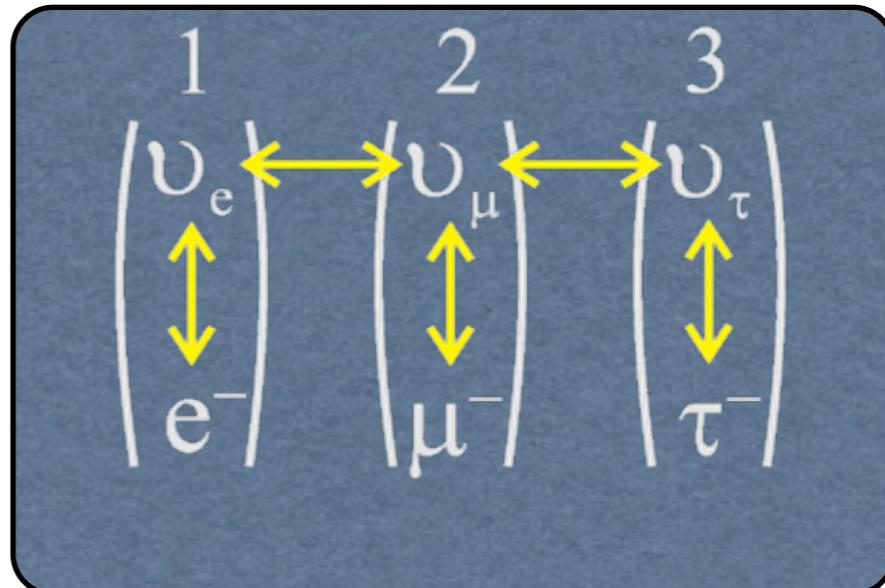
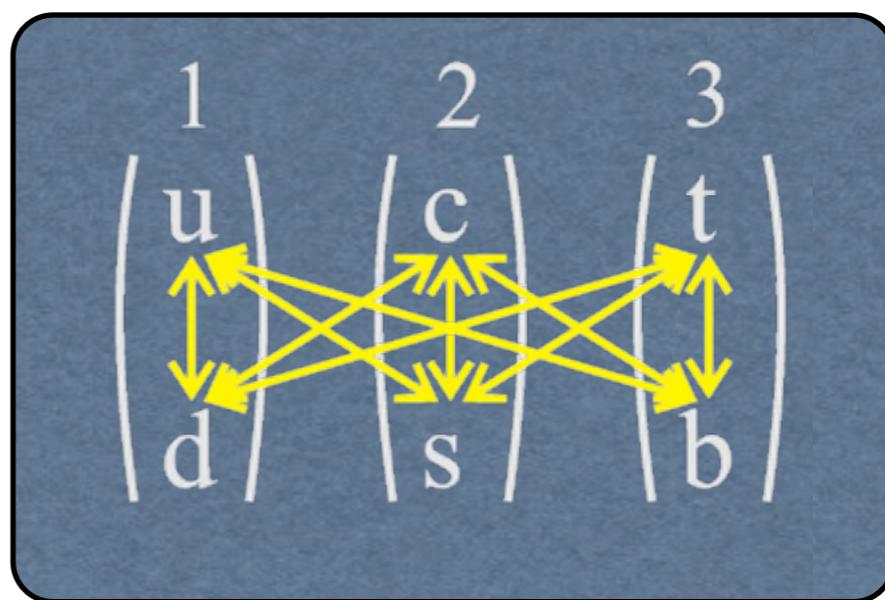


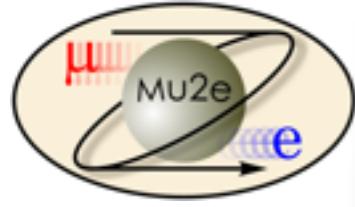


# Flavor oscillations

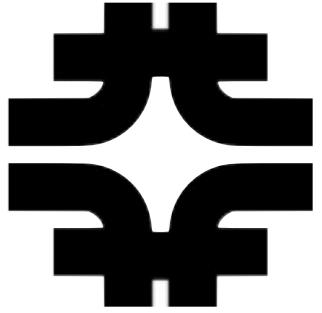


- Maybe the most important feature of the SM
  - ◆ why are 3 families anyway?
- Quarks change flavor (CKM), neutral leptons change flavor (MNS)
- Do charged leptons oscillate? (CLFV)
  - ◆ answer:

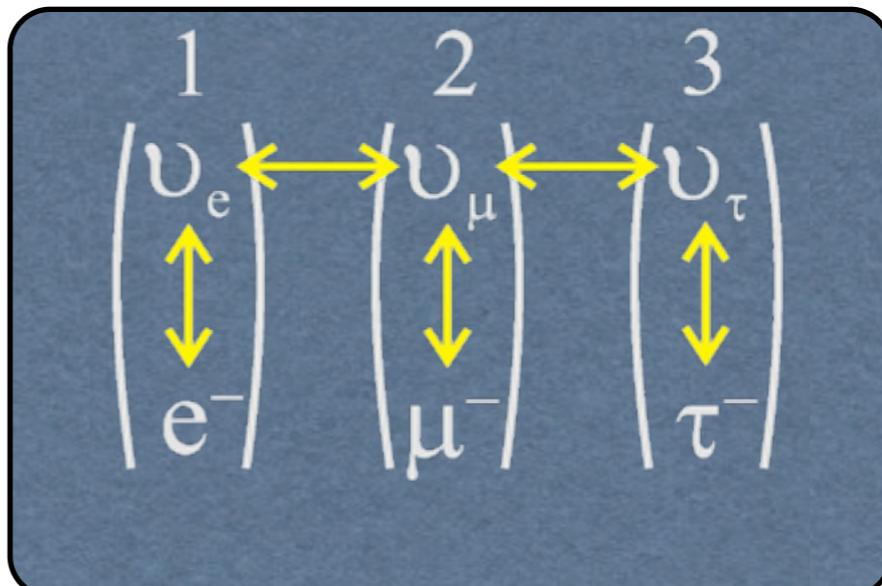
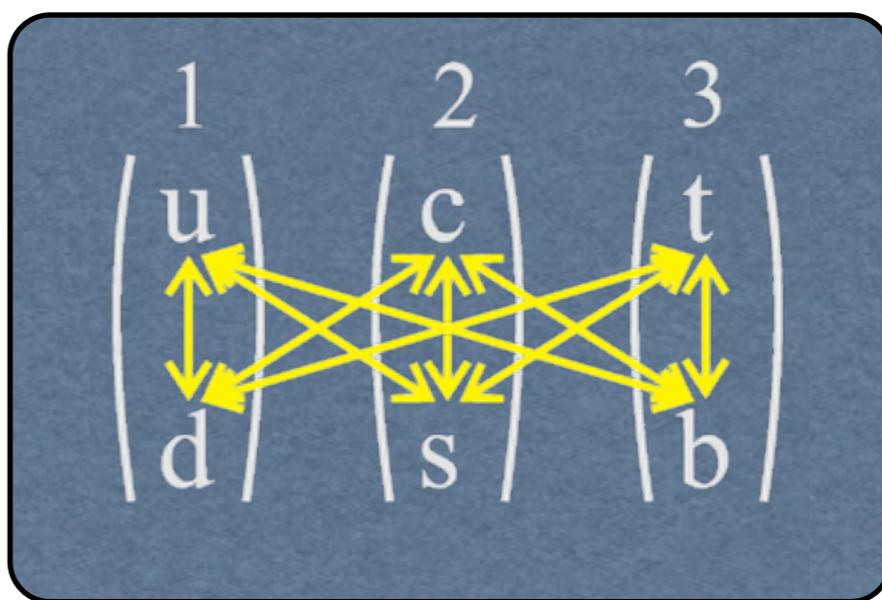


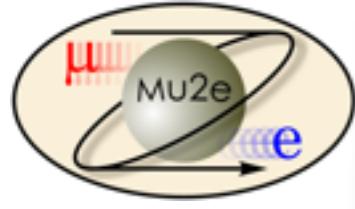


# Flavor oscillations

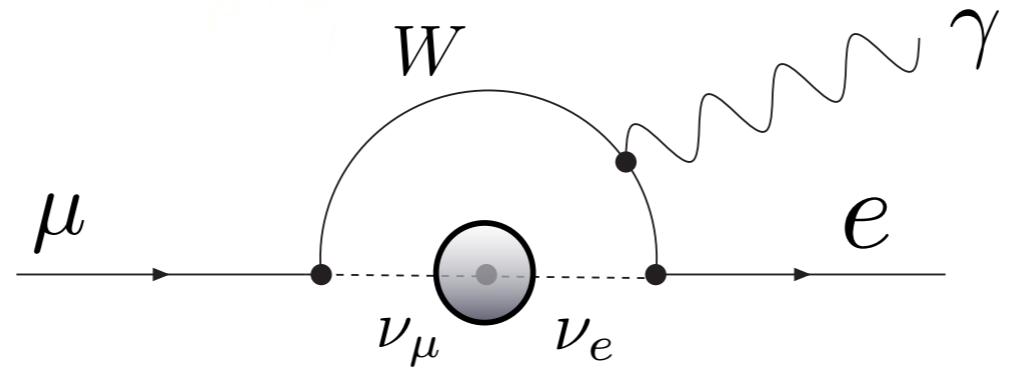
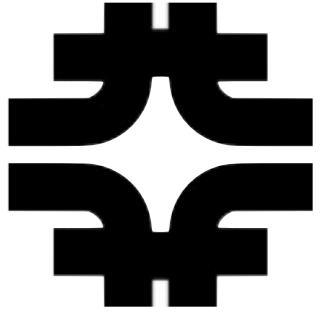


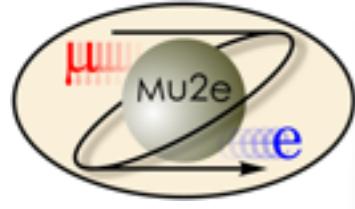
- Maybe the most important feature of the SM
  - ◆ why are 3 families anyway?
- Quarks change flavor (CKM), neutral leptons change flavor (MNS)
- Do charged leptons oscillate? (CLFV)
  - ◆ answer: **YES**



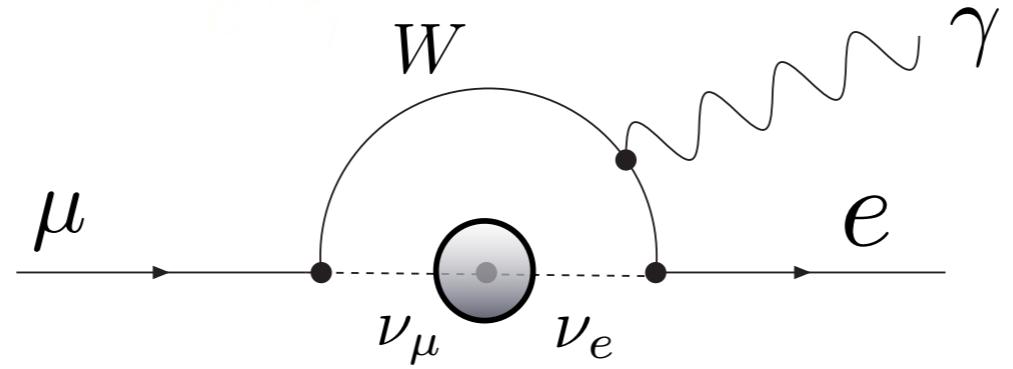
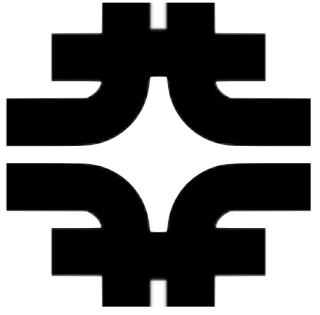


# Neutrinos have mass

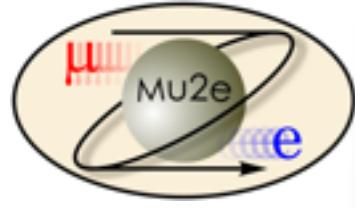




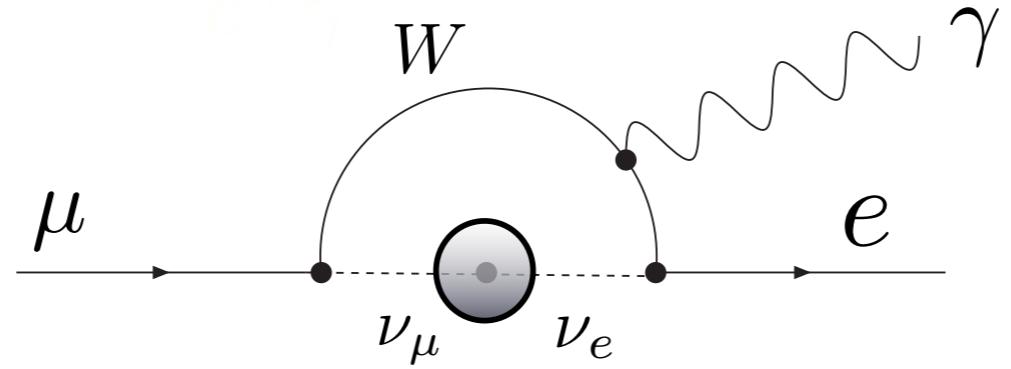
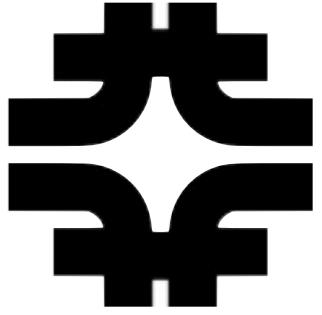
# Neutrinos have mass



$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

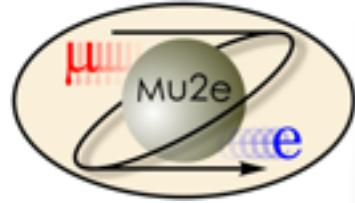


# Neutrinos have mass

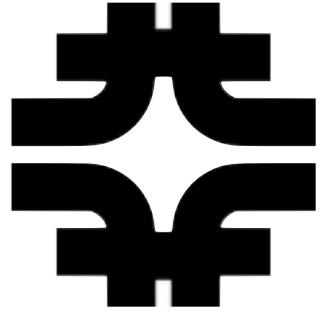


$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

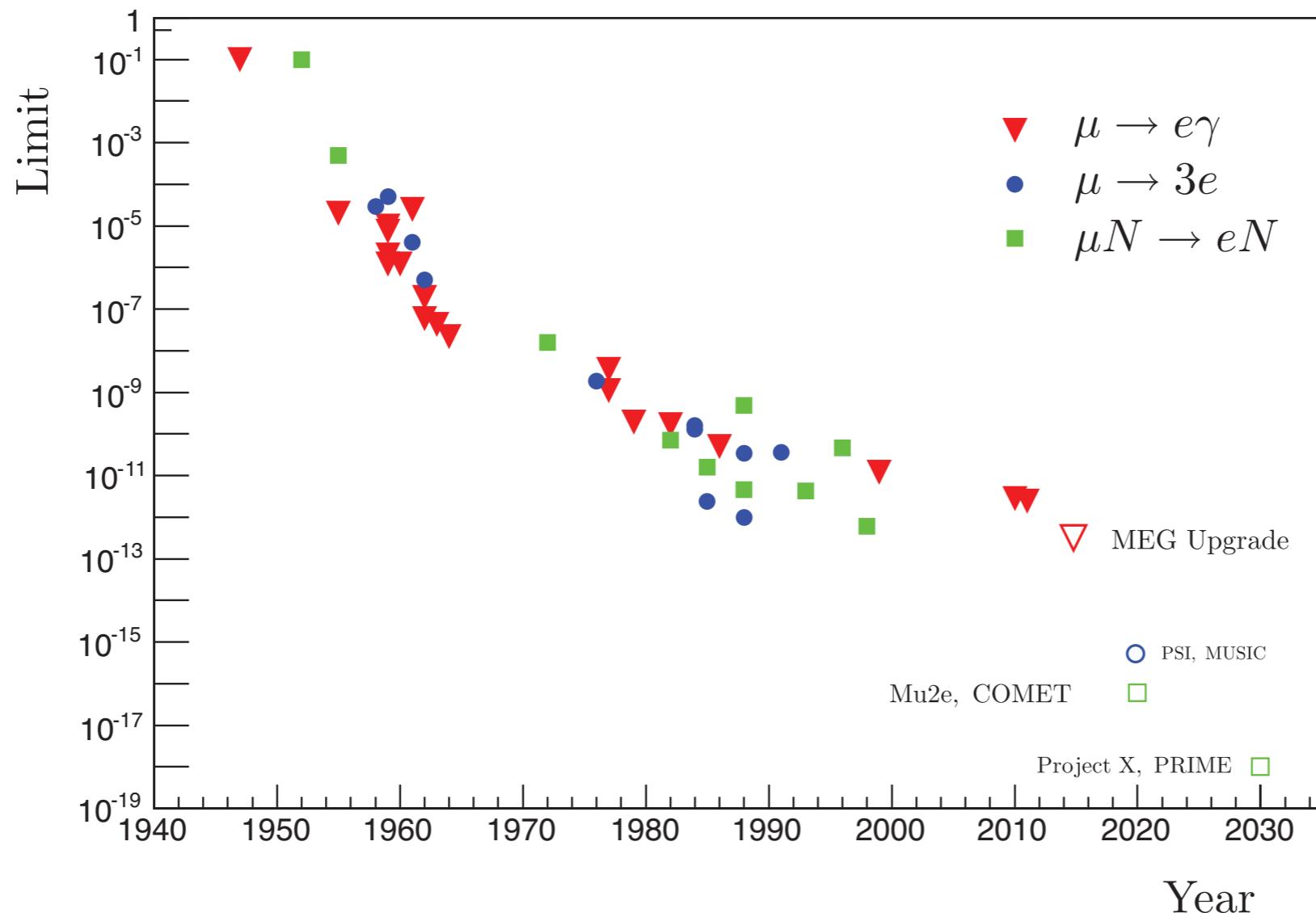
- not going to measure this one soon

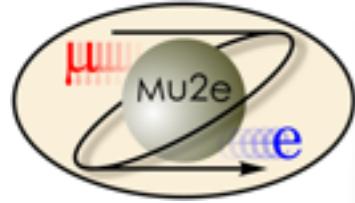


# History

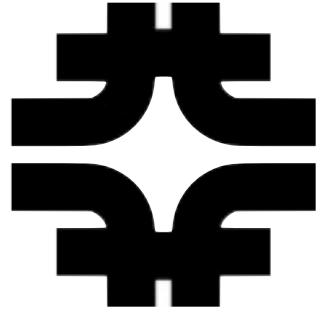


- CLFV: not a new idea
- In fact, almost everyone looked for this

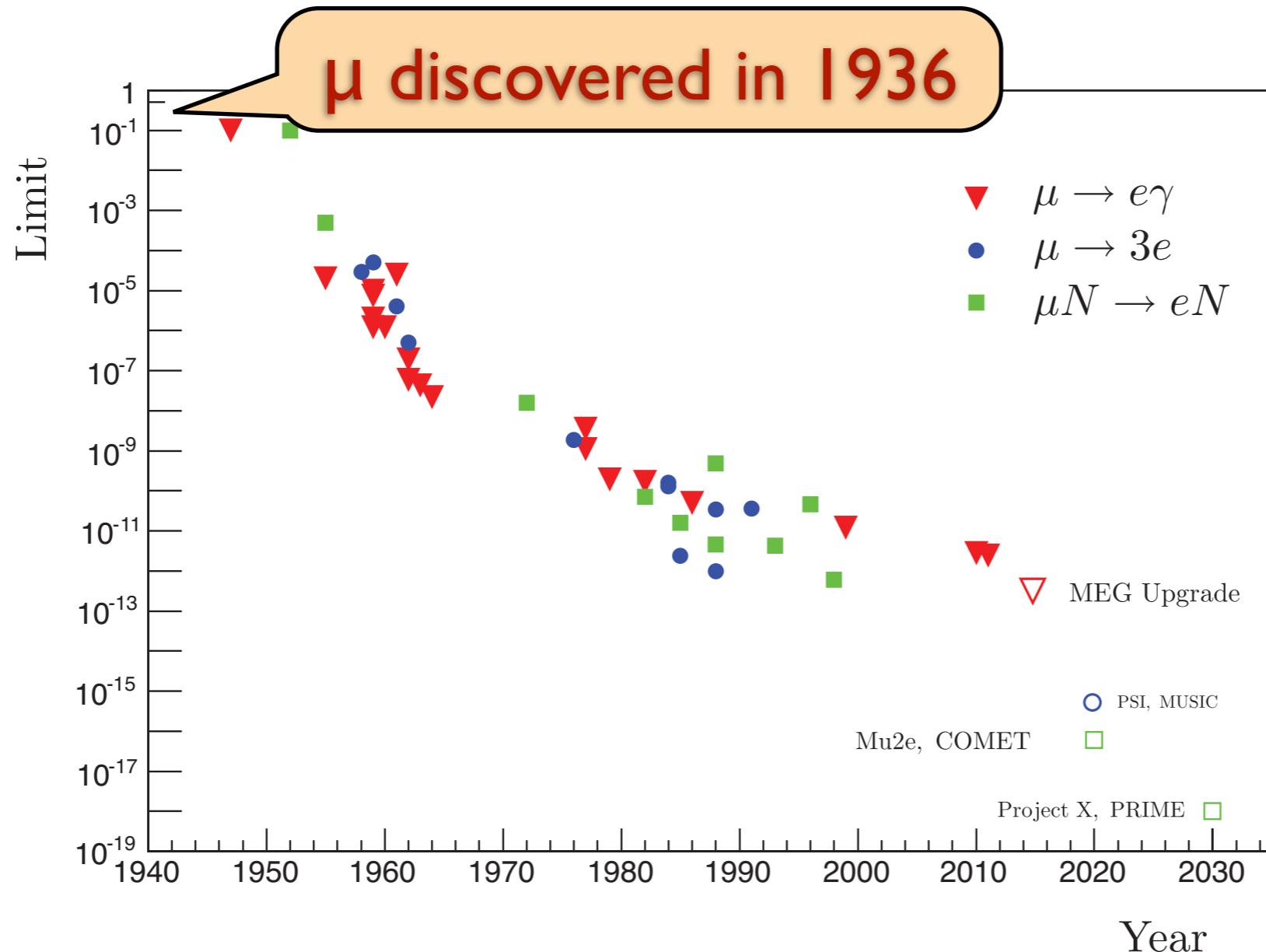


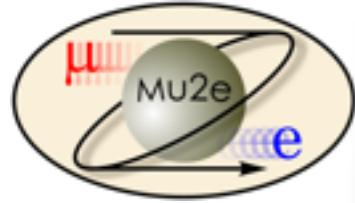


# History

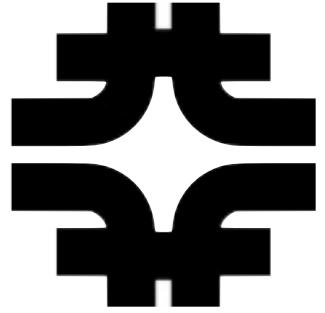


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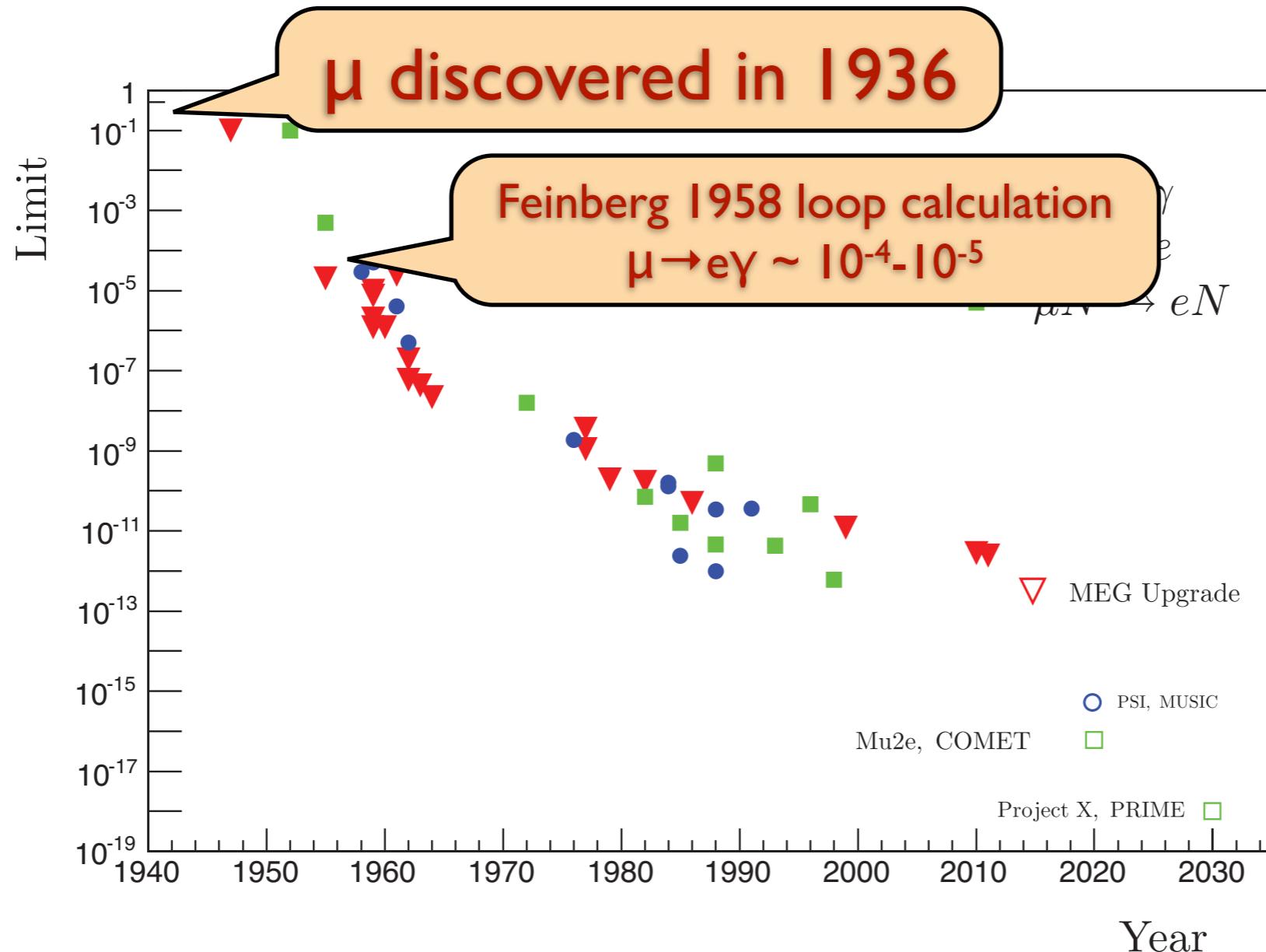


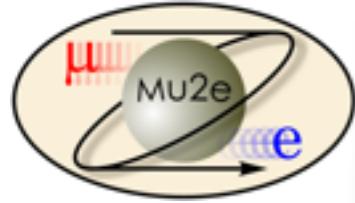


# History

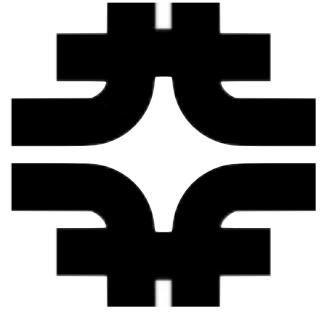


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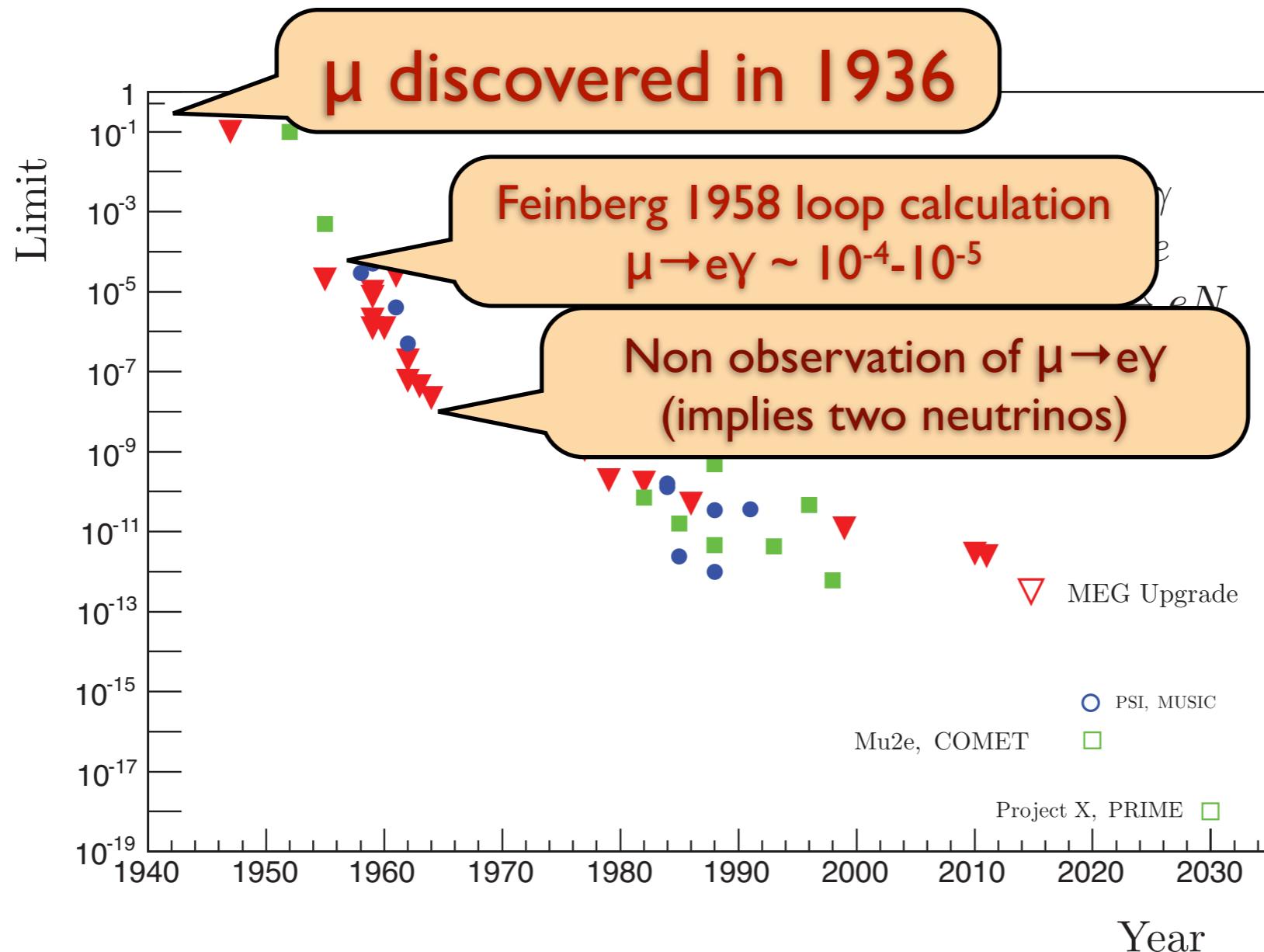


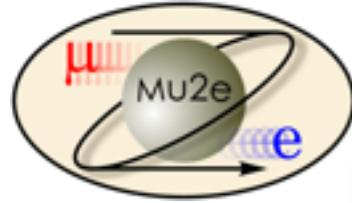


# History

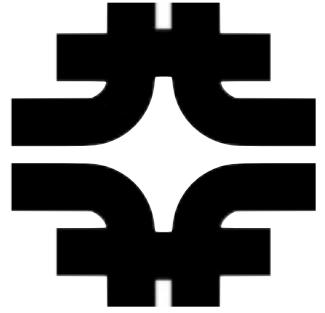


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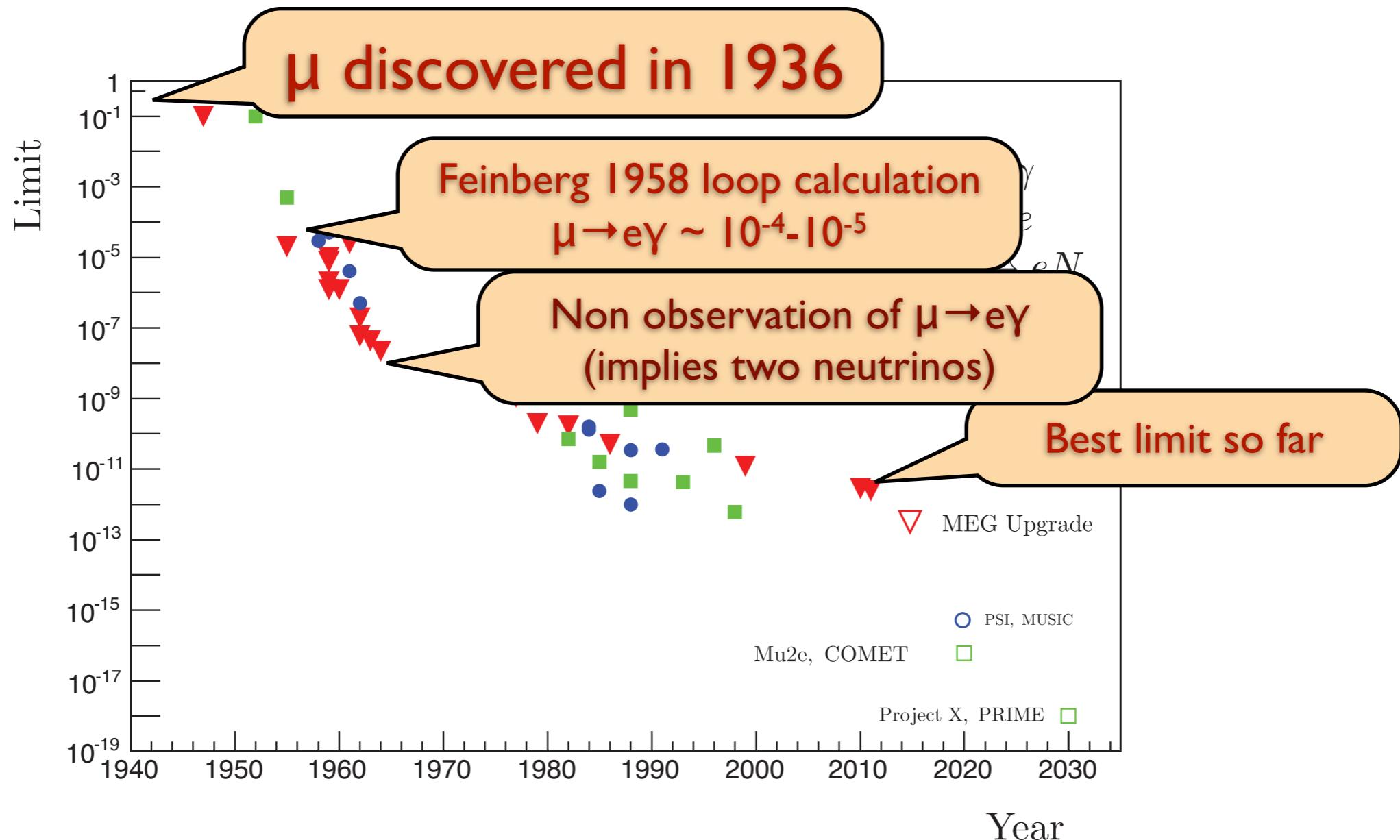


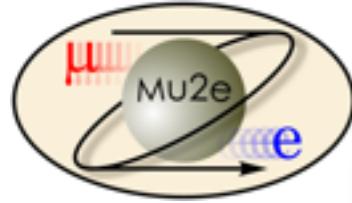


# History

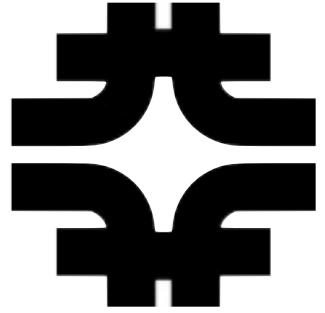


- CLFV: not a new idea
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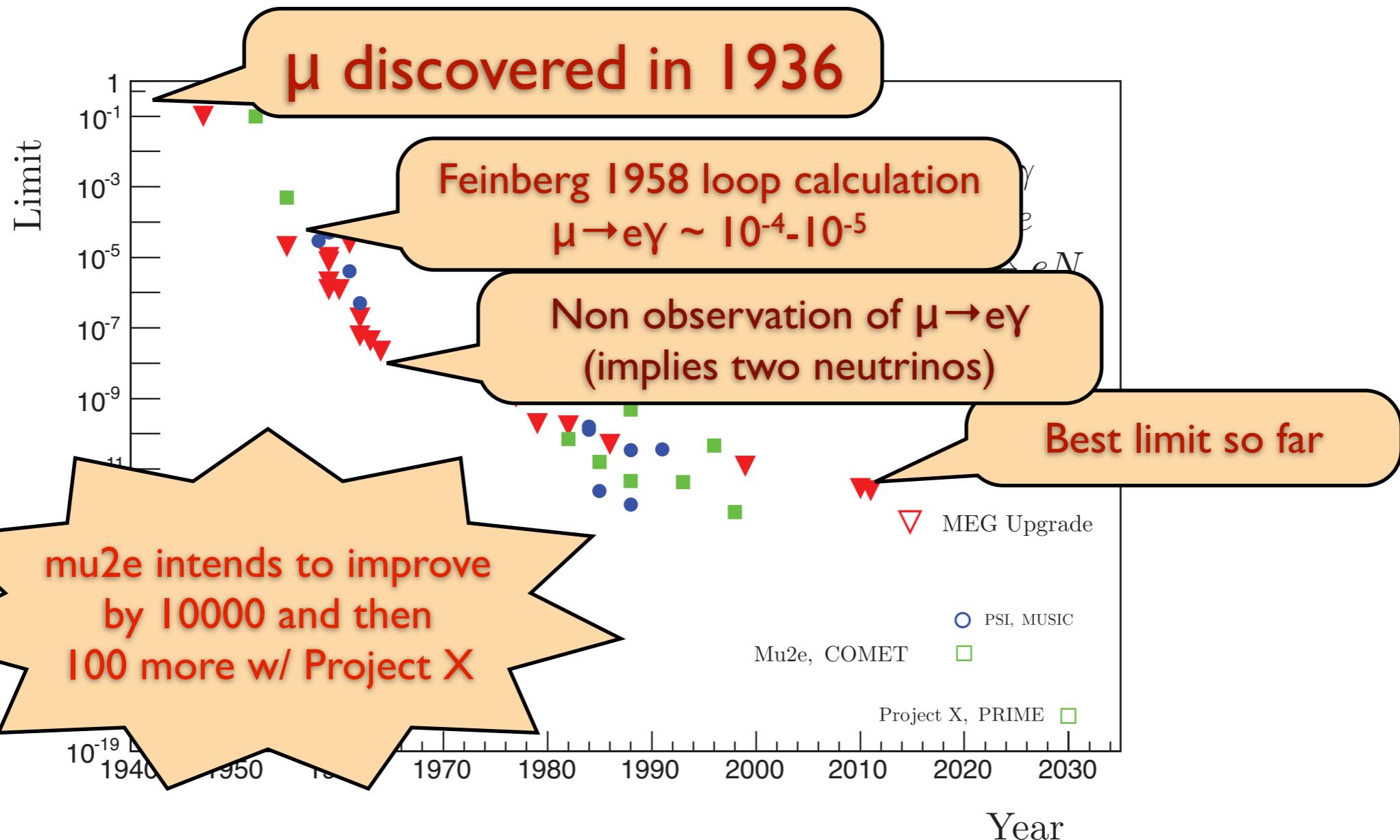


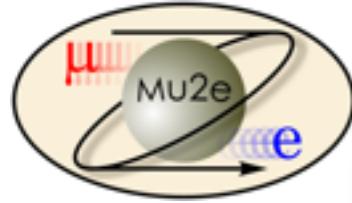


# History

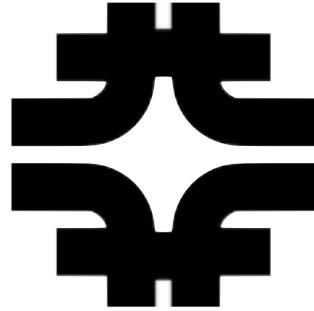


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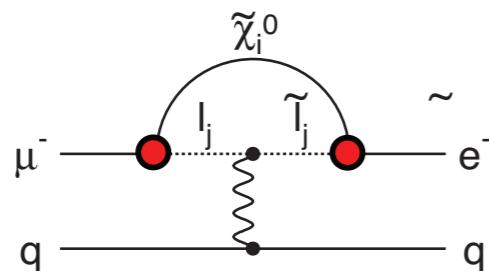


# New physics



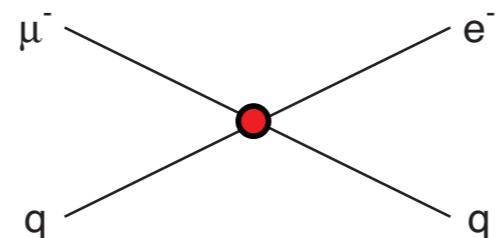
## Supersymmetry

rate  $\sim 10^{-15}$



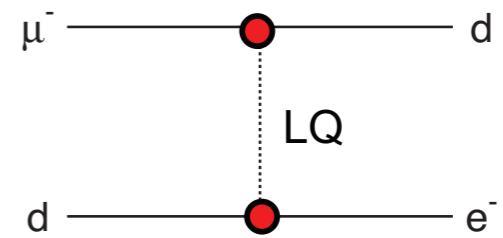
## Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$



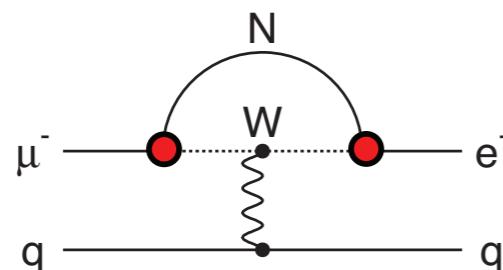
## Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$$



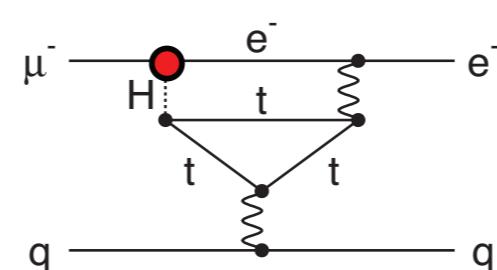
## Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



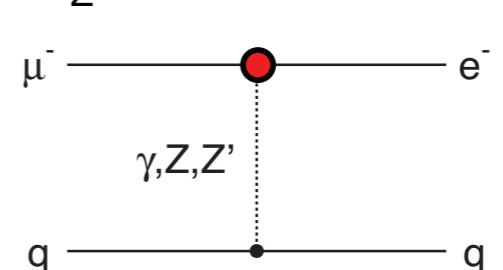
## Second Higgs Doublet

$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$$

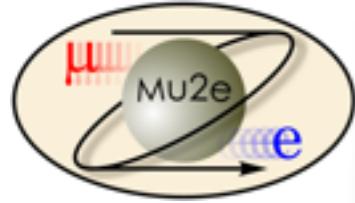


## Heavy Z' Anomalous Z Coupling

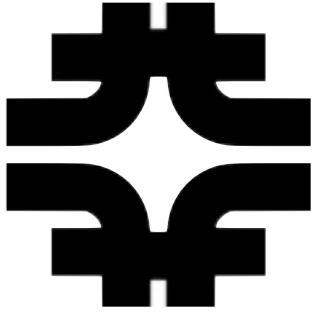
$$M_{Z'} = 3000 \text{ TeV}/c^2$$



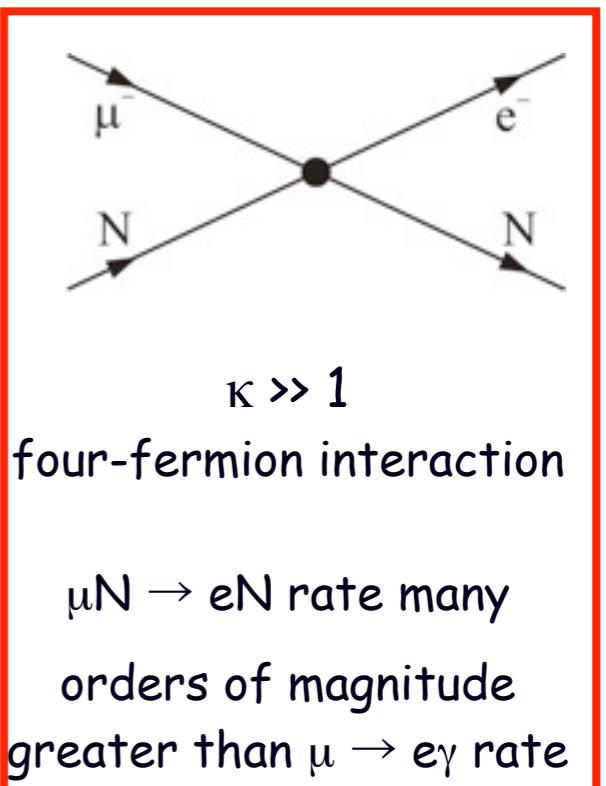
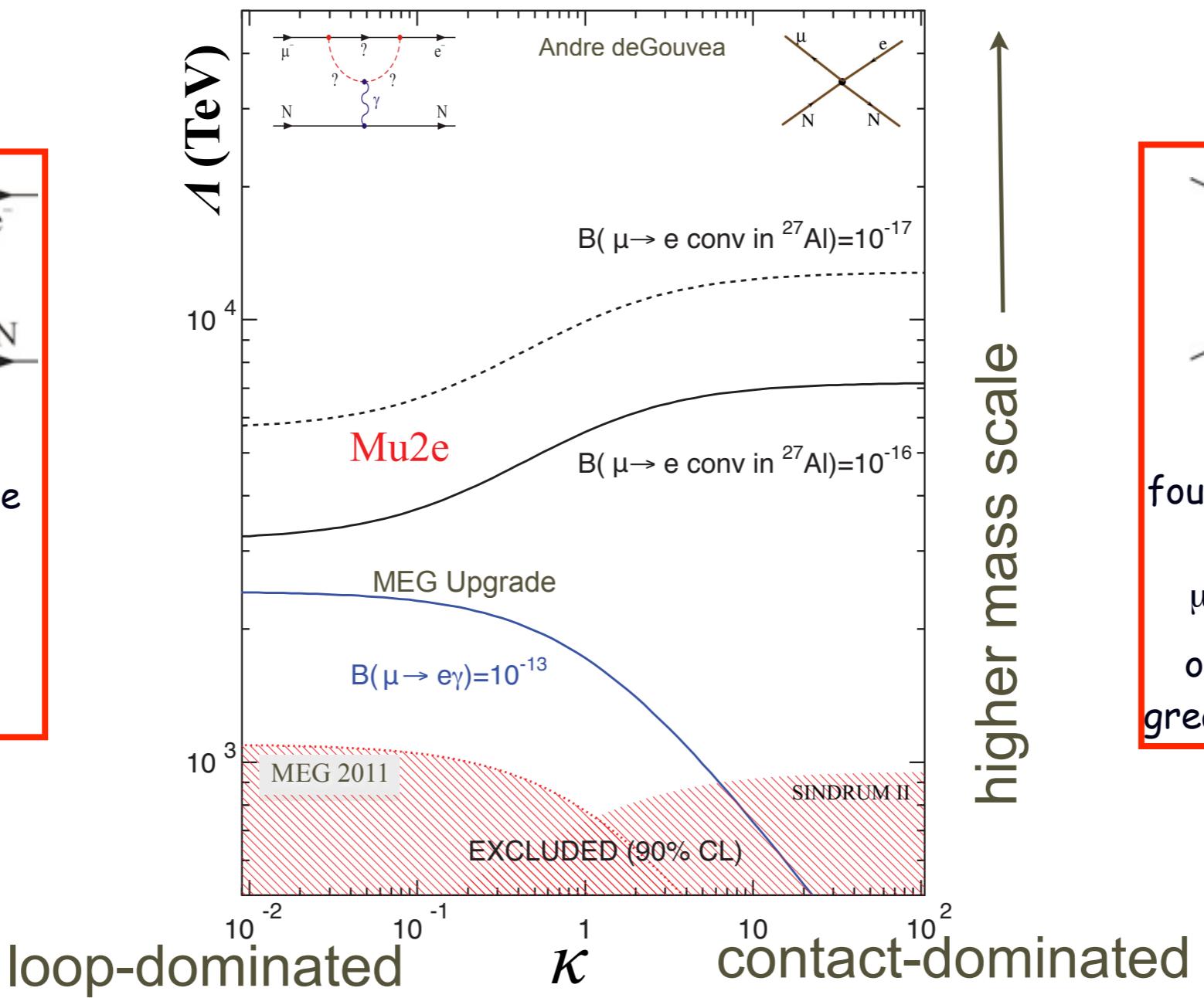
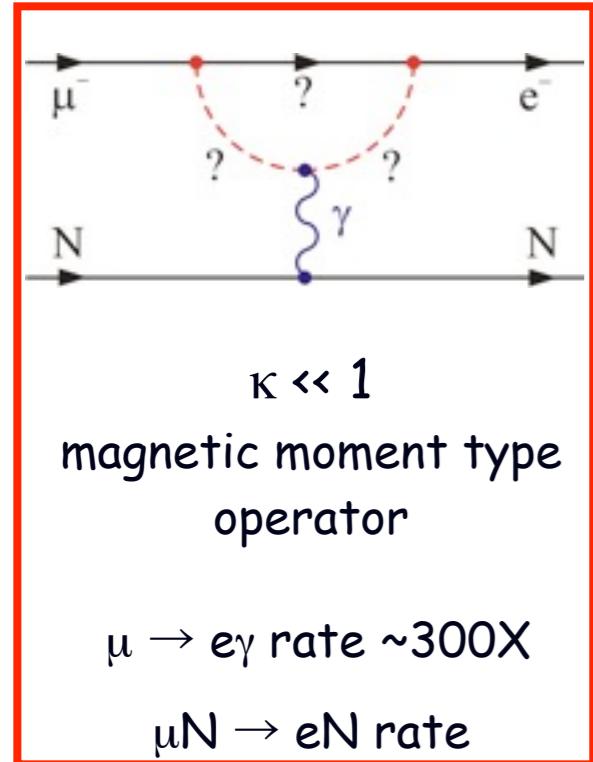
also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)  
and Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:[10.1146/annurev.nucl.58.110707.171126](https://doi.org/10.1146/annurev.nucl.58.110707.171126)

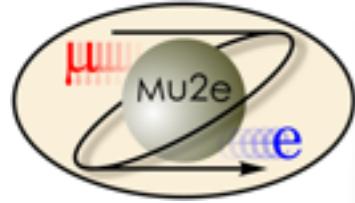


# Model independent

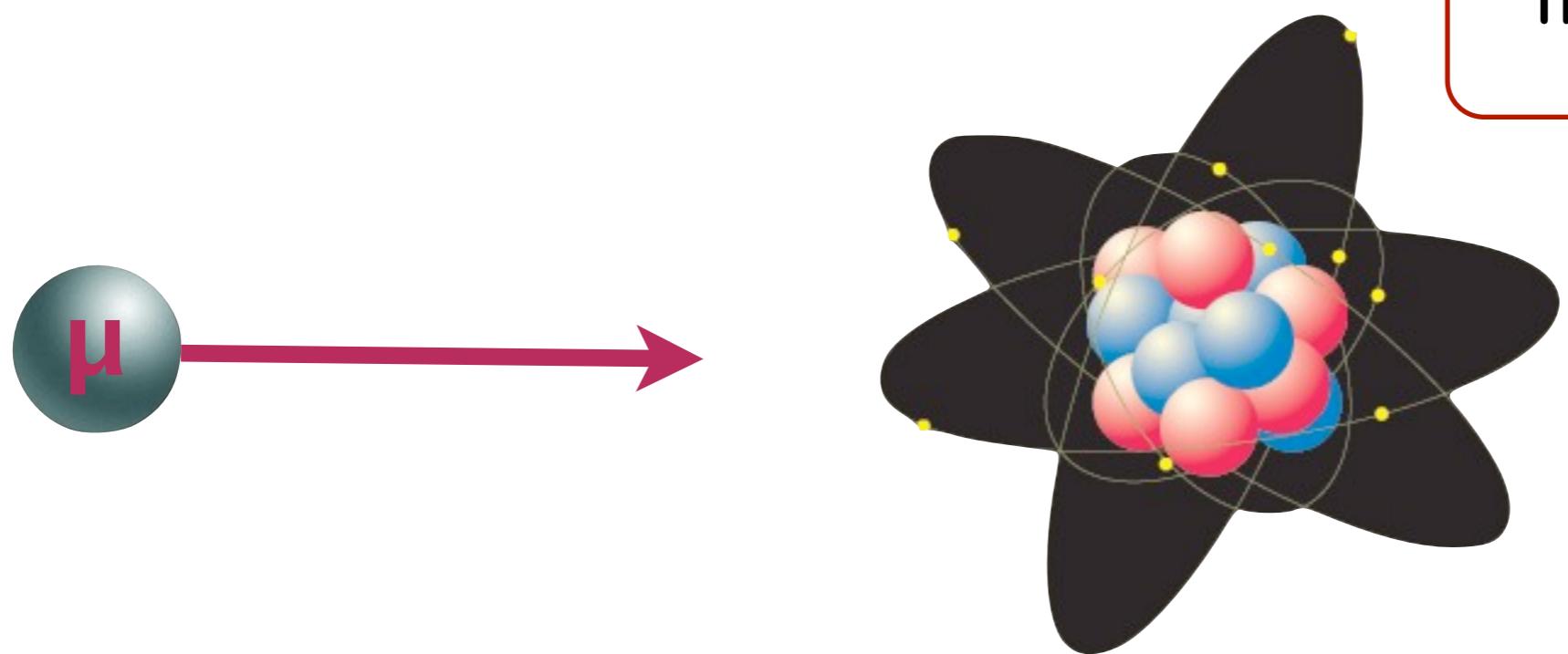
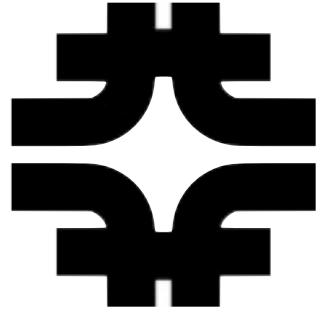


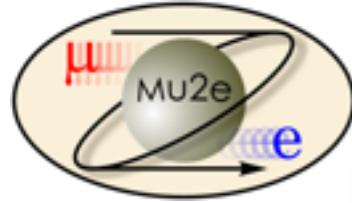
$$L = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$



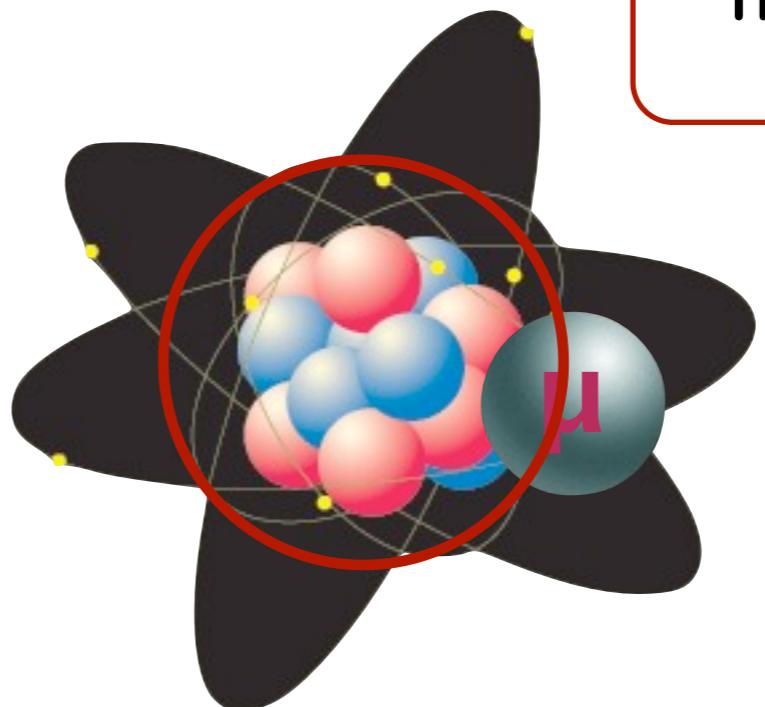
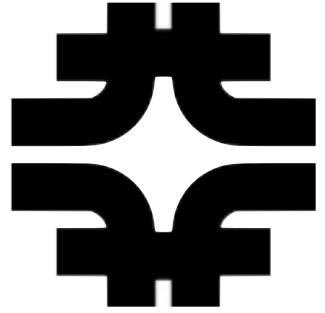


# Muon to electron conversion



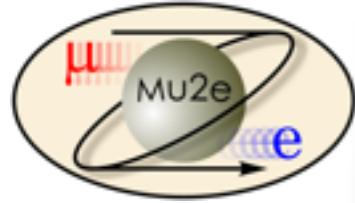


# Muon to electron conversion

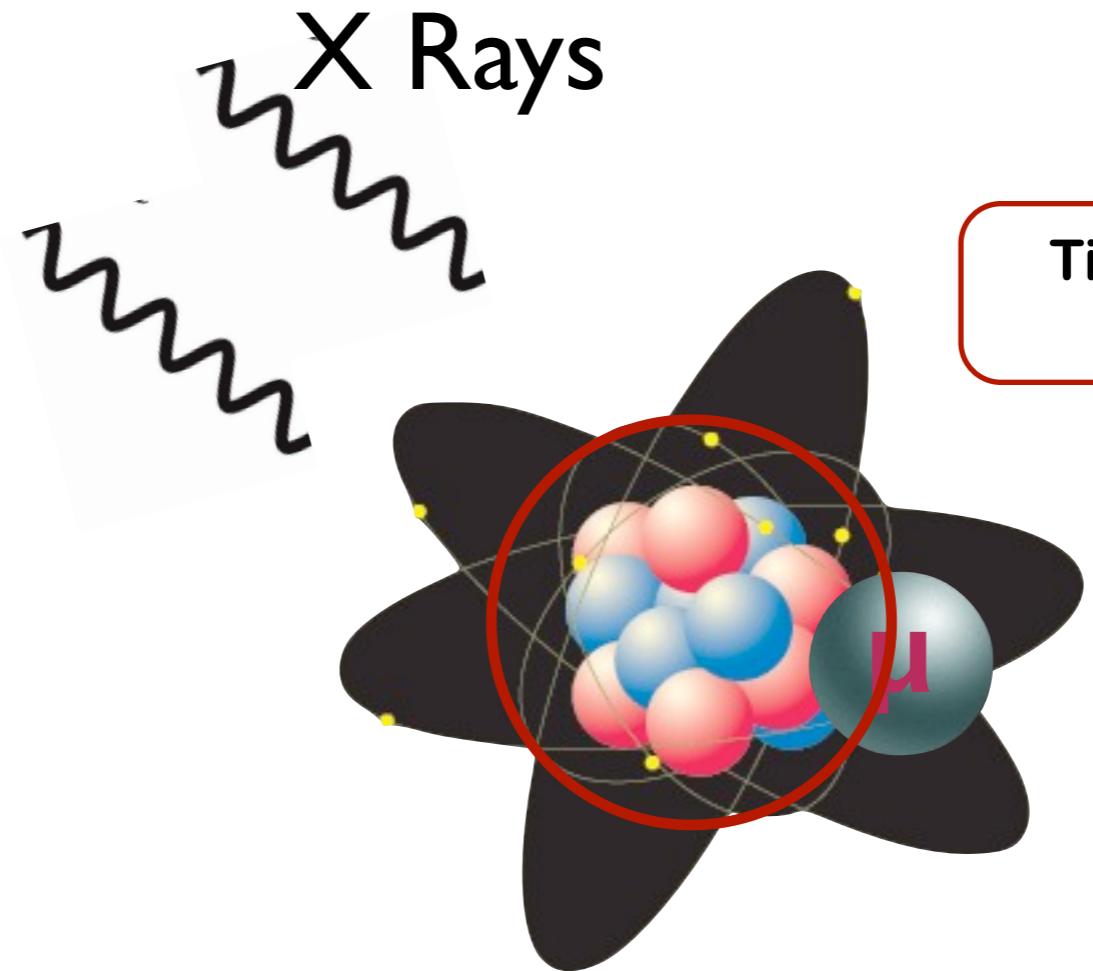
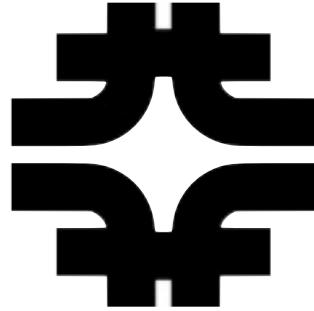


Time scale for entire process  $\sim \mu\text{s}$

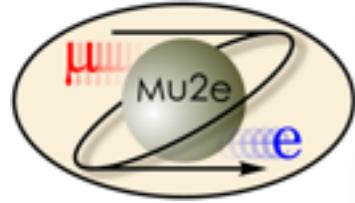
- muons captured on target
  - ◆ formation of atomic muon



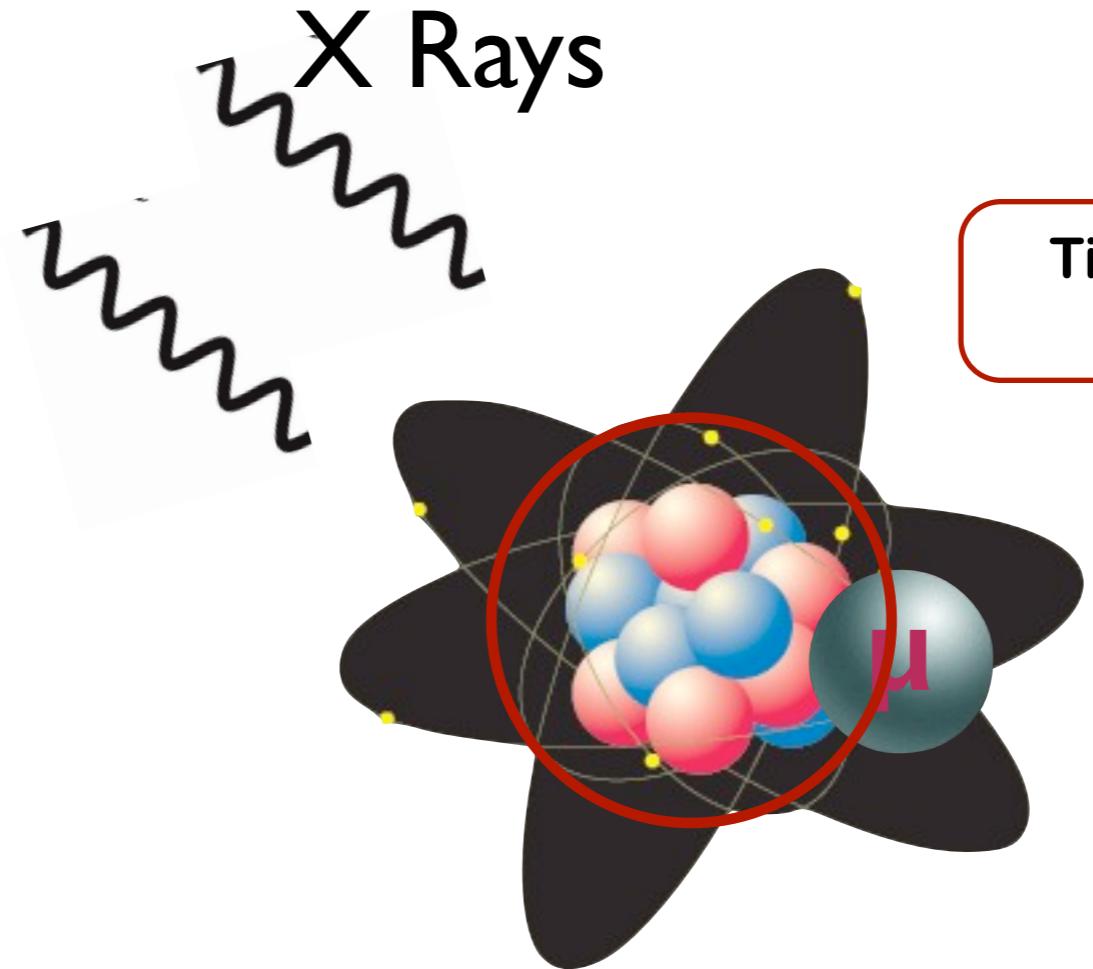
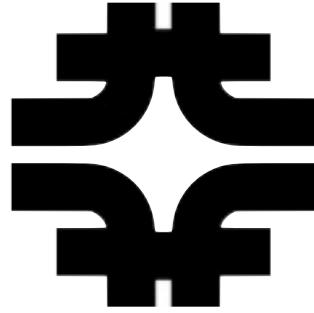
# Muon to electron conversion



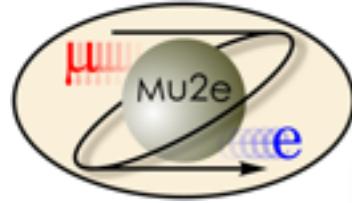
- muons captured on target
  - ◆ formation of atomic muon
  - ◆ immediately ( $\sim \text{ps}$ ) falls to 1s (X rays) → normalization



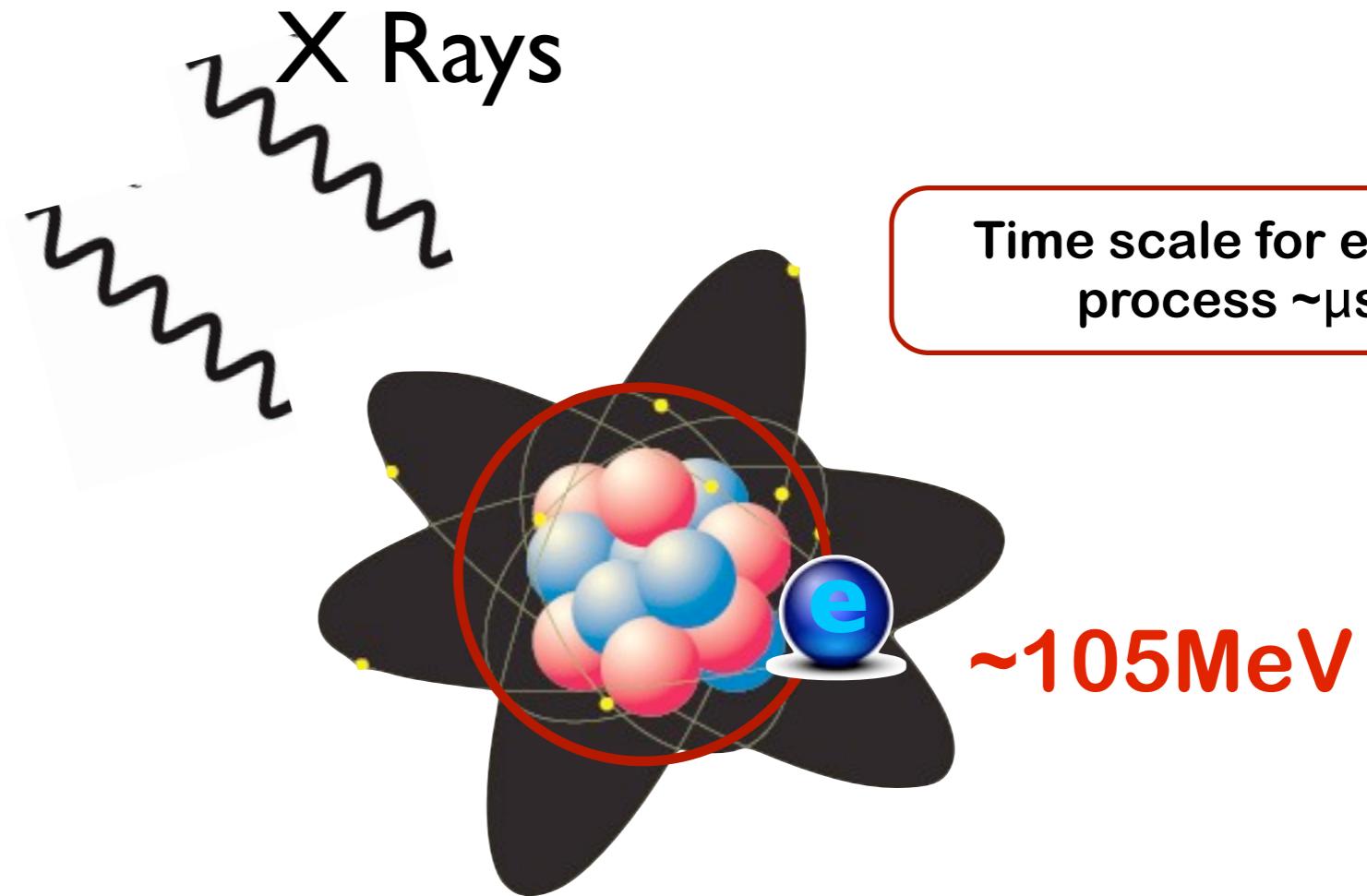
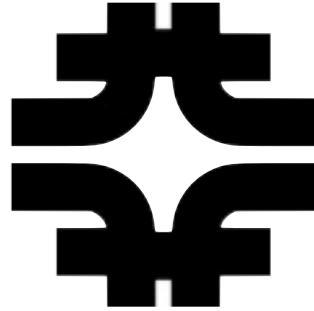
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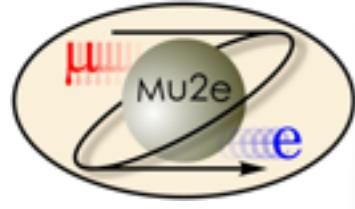
- muons captured on target
  - ◆ formation of atomic muon
  - ◆ immediately (~ps) falls to 1s (X rays) → normalization
- the Bohr radius is 20fm → muon sees nucleus (~4fm)



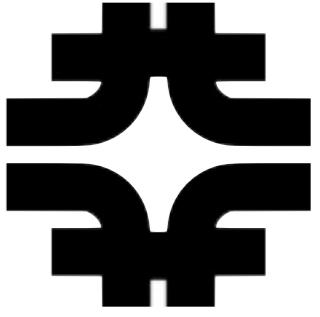
# Muon to electron conversion



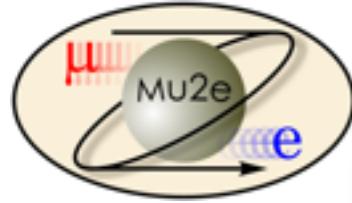
- muons captured on target
  - ◆ formation of atomic muon
  - ◆ immediately (~ps) falls to 1s (X rays) → normalization
- the Bohr radius is 20fm → muon sees nucleus (~4fm)
- conversion electron ~105MeV
  - ◆ correct for recoil and BE



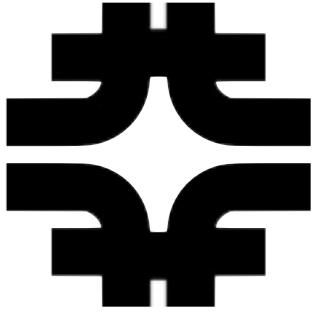
# But what really happens...



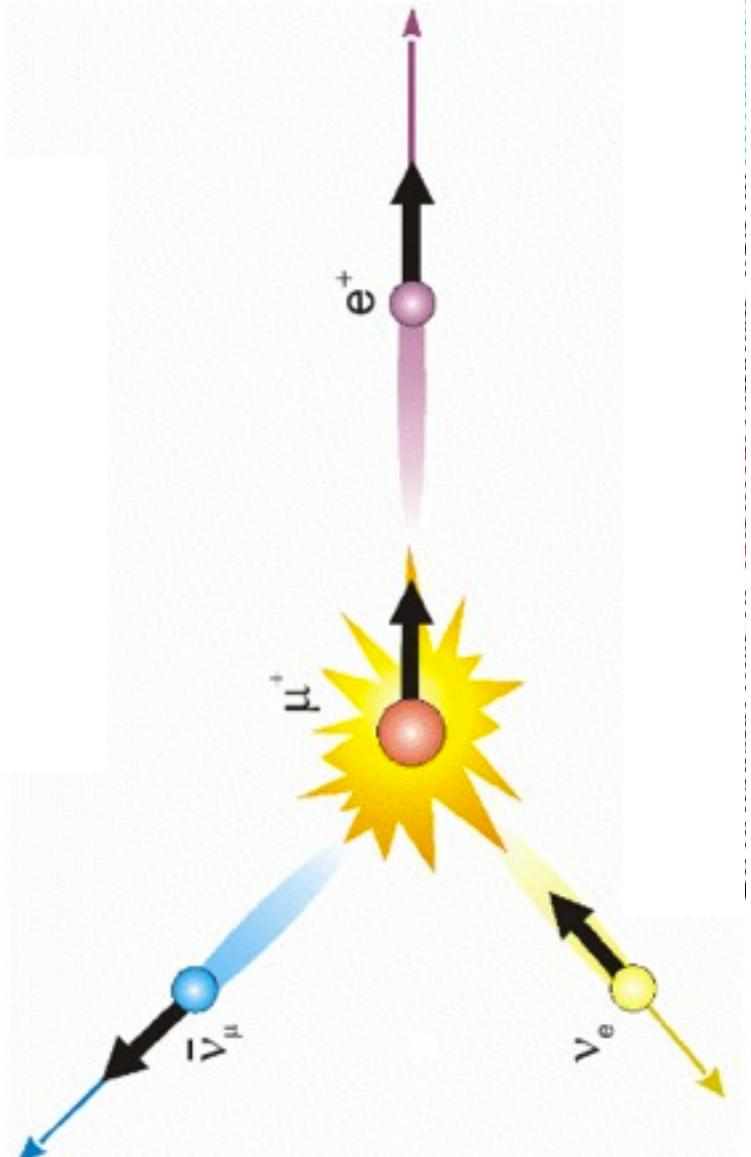
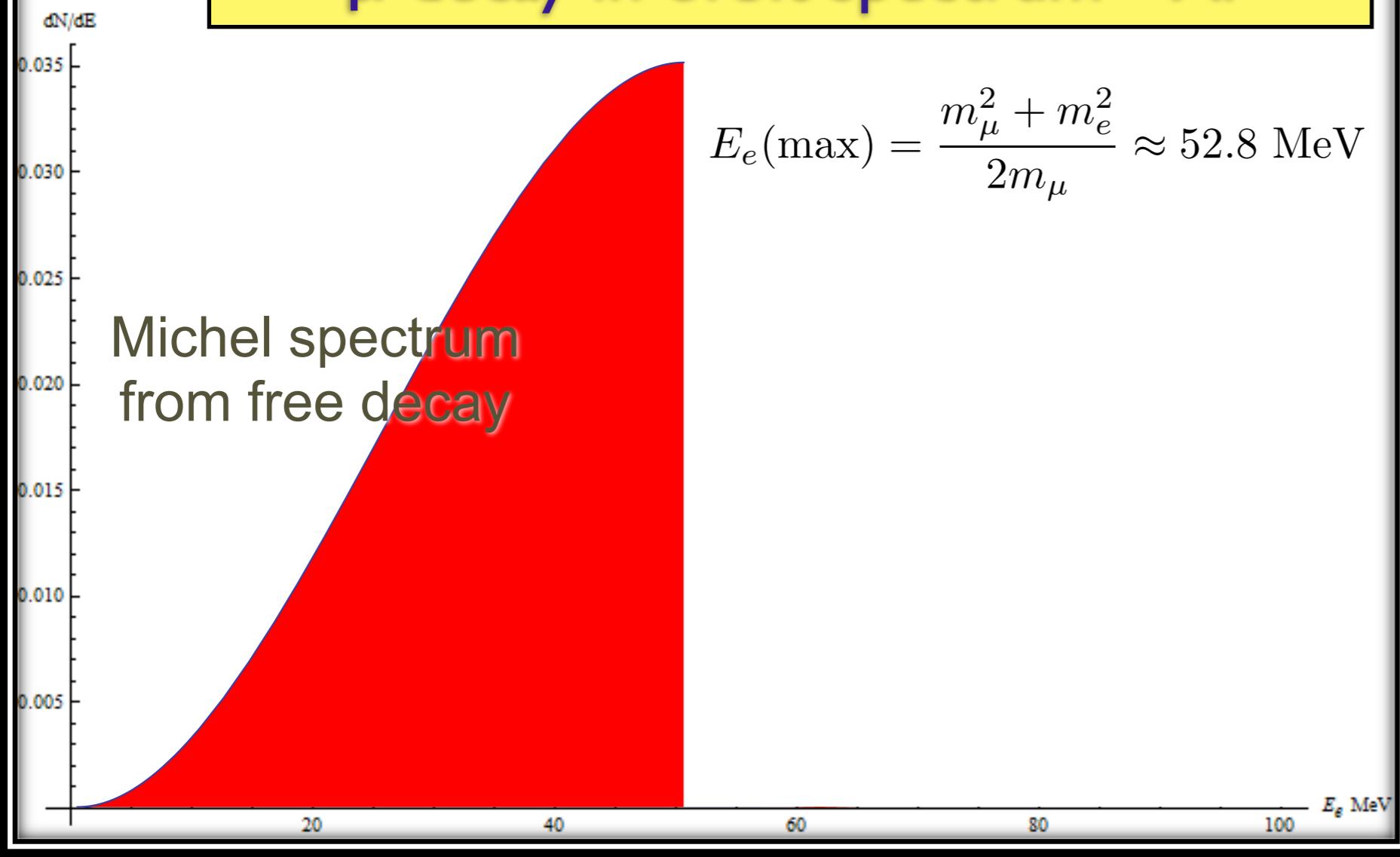
- Muon decay in orbit
- Nuclear muon capture

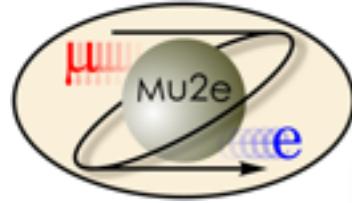


# Muon decay

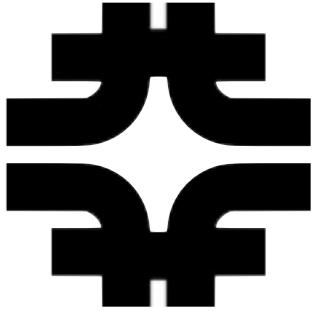


$\mu$  decay in orbit spectrum  $^{27}\text{Al}$

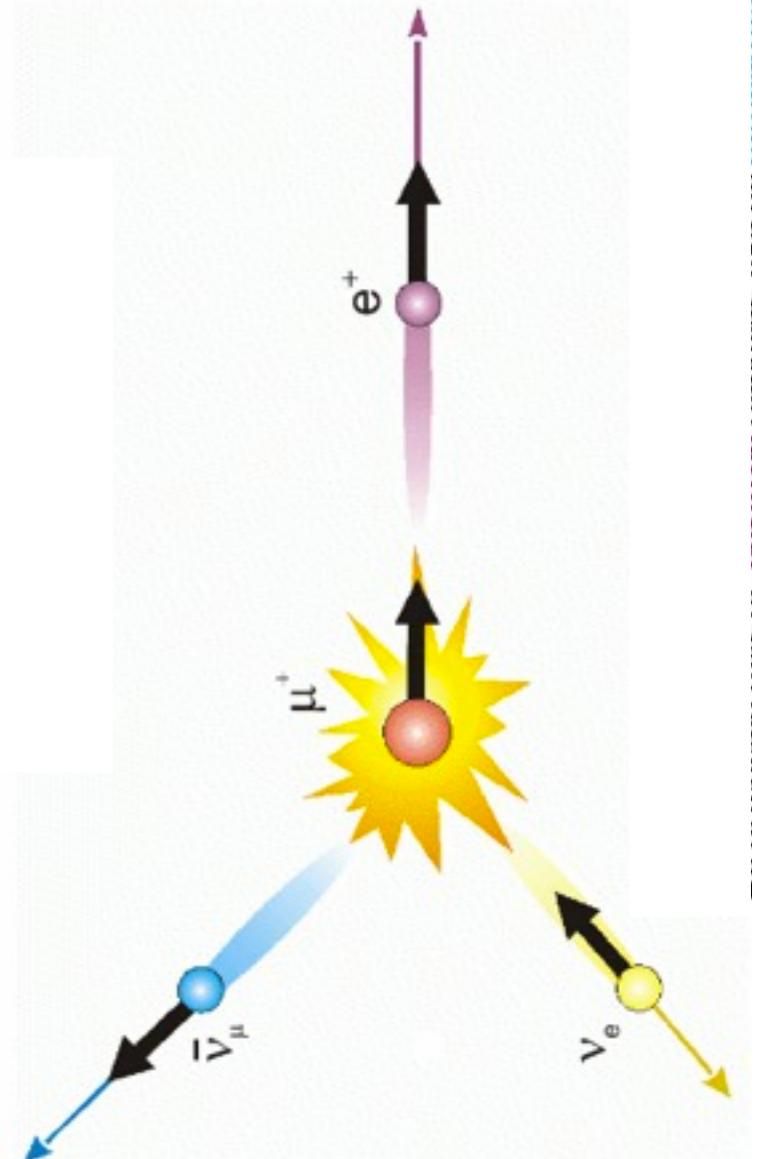
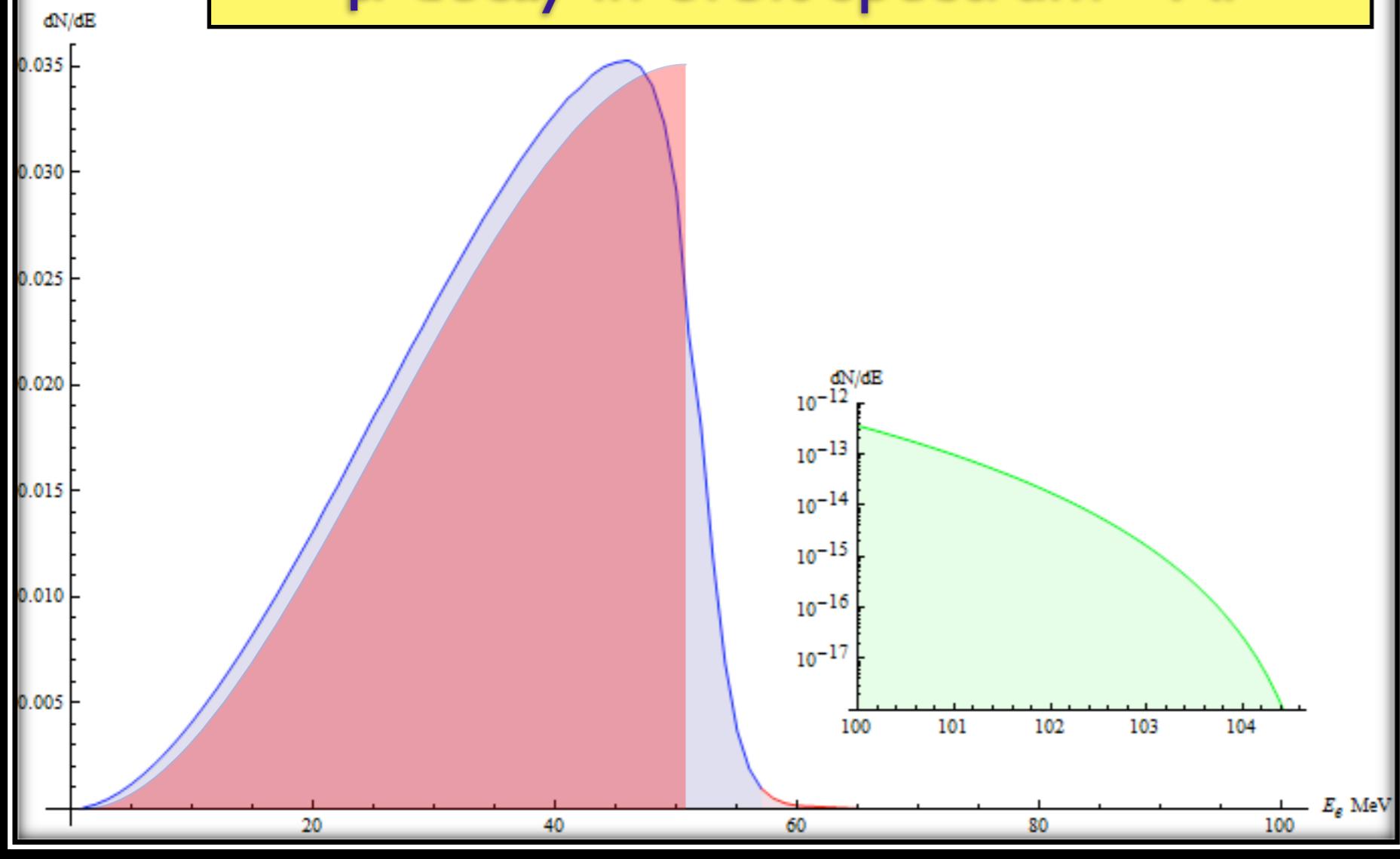


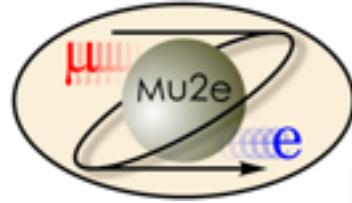


# Muon decay

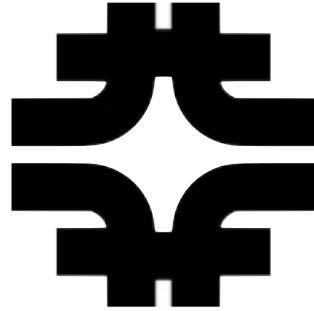


$\mu$  decay in orbit spectrum  $^{27}\text{Al}$

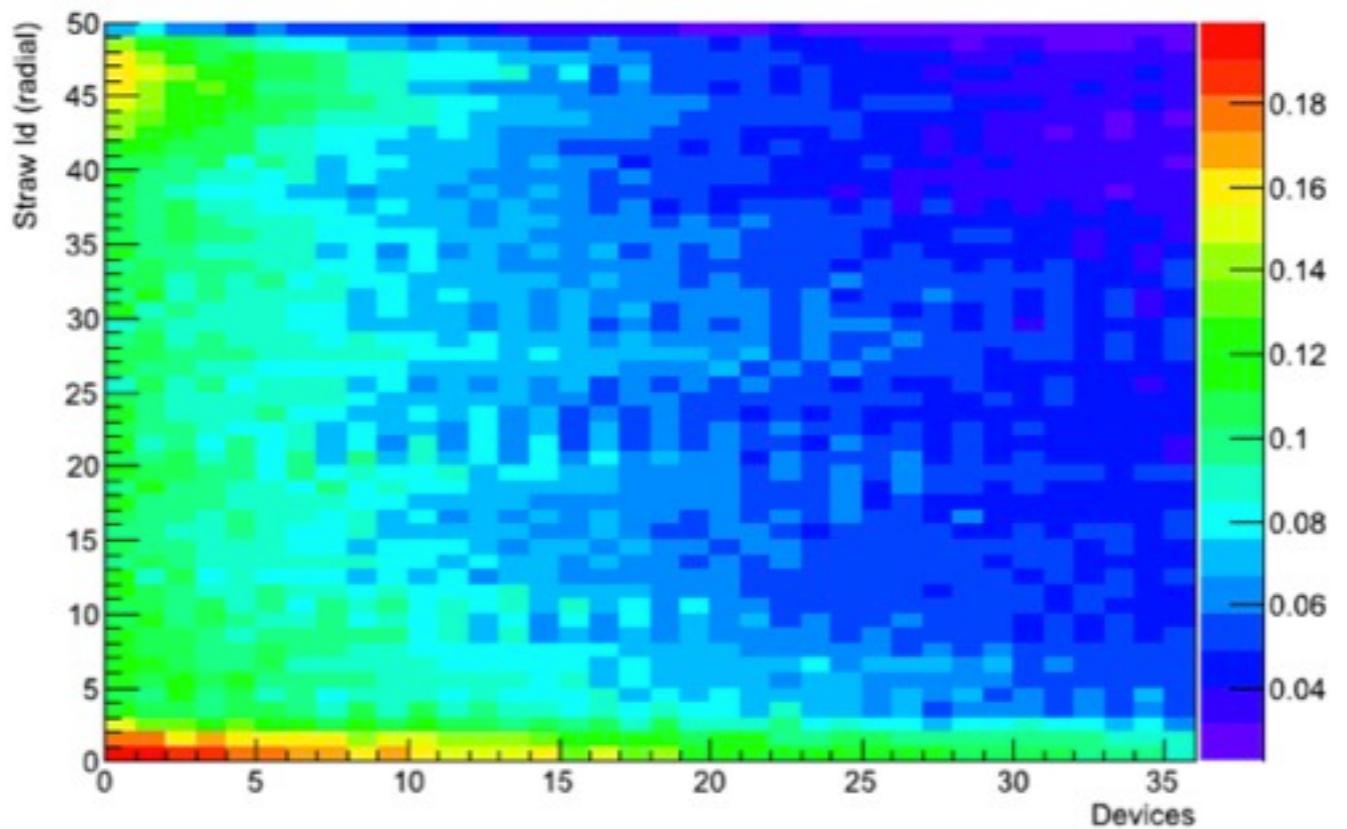
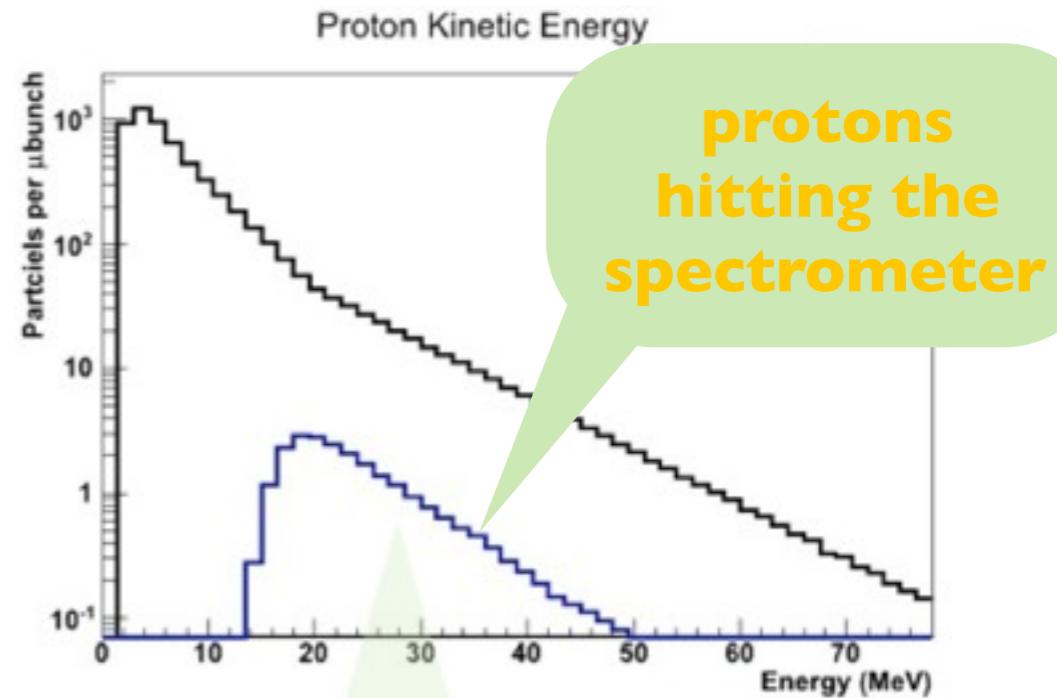


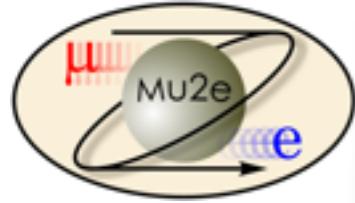


# Nuclear muon capture

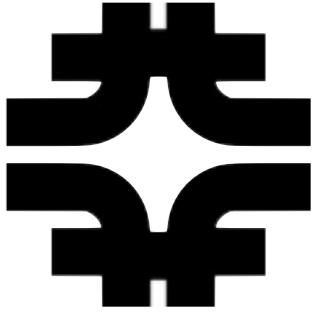


- $\mu + A(Z, N) \rightarrow \nu_\mu + A(Z', N') + an + bp + c\gamma$ 
  - ◆ For Al:  $a \approx 1.5$ ,  $b \approx 0.1$ ,  $c \approx 2$
- **protons** are easy to reconstruct but
  - ◆ 20-30x more ionizing  $\rightarrow$  high charge
  - ◆ spurious hits
- **neutrons** are not a direct tracking problem but
  - ◆ high fluences affect detectors
  - ◆ can knock out electrons, photons
- **$\gamma$ 's** can convert into  $e^+e^-$



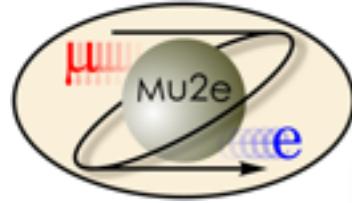


# ...and other processes

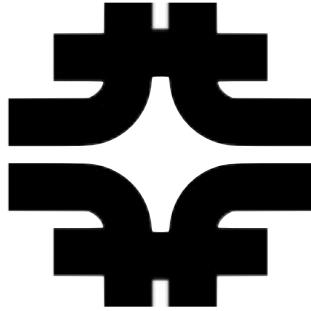


- Muon decay in orbit
- Nuclear muon capture
- and others:
  - ◆ radiative pion captures
  - ◆ beam electrons, antiprotons
  - ◆ in flight  $\mu$  and  $\pi$  decays
  - ◆ cosmic rays



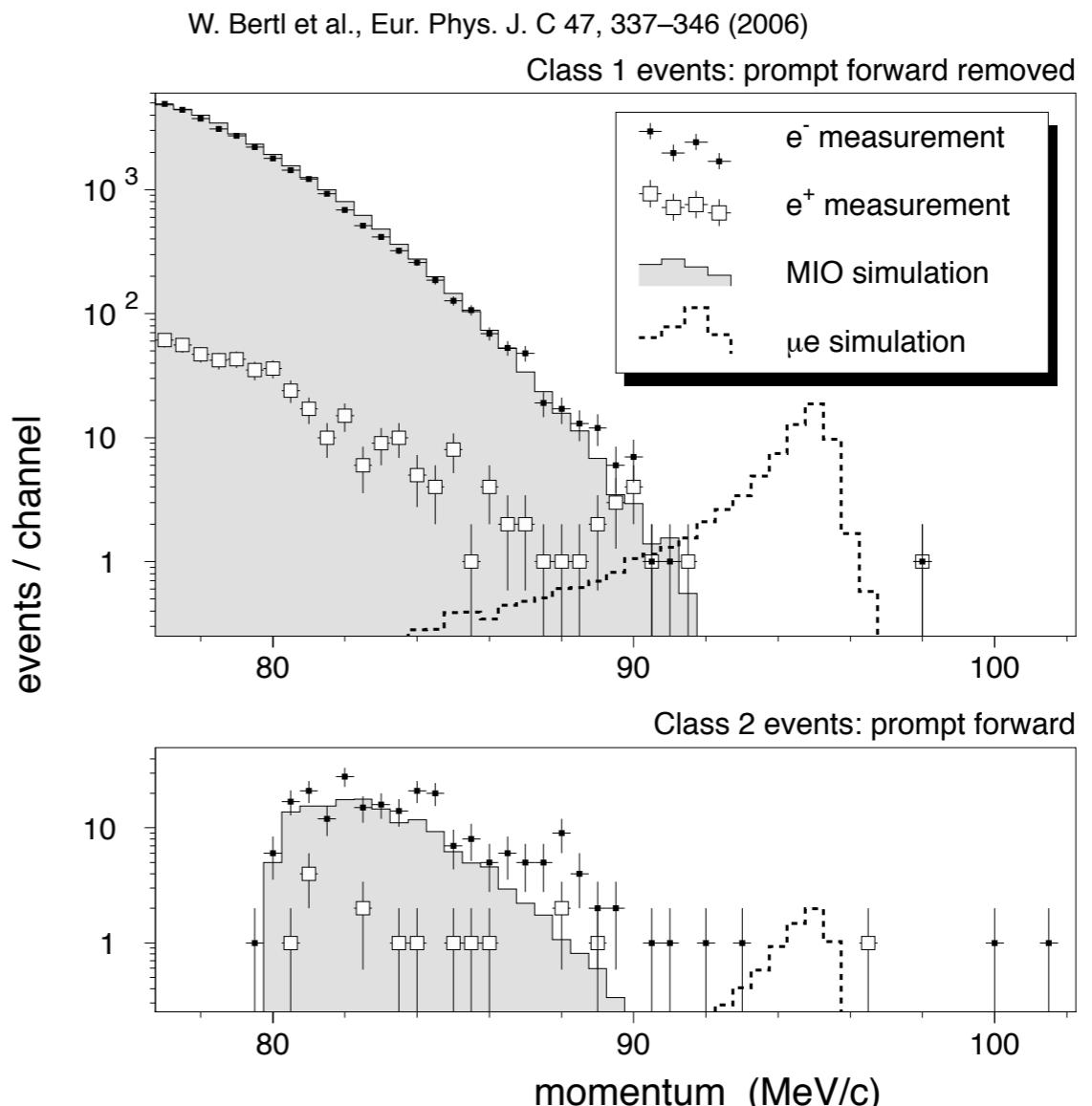


# Current state of the art

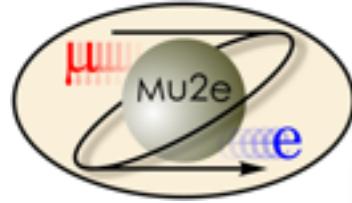


## SINDRUMII at PSI

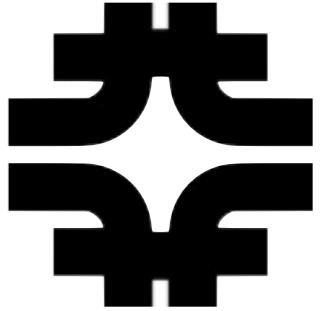
- Final Run on Au at PSI
  - ◆  $R_{\mu e} < 7 \times 10^{-13}$
- 1 event past the end of the spectrum
- radiative pions, CR?
- PSI has a DC beam - more on this later

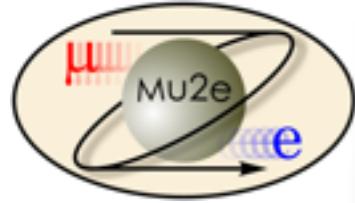


$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z', N') + X}$$

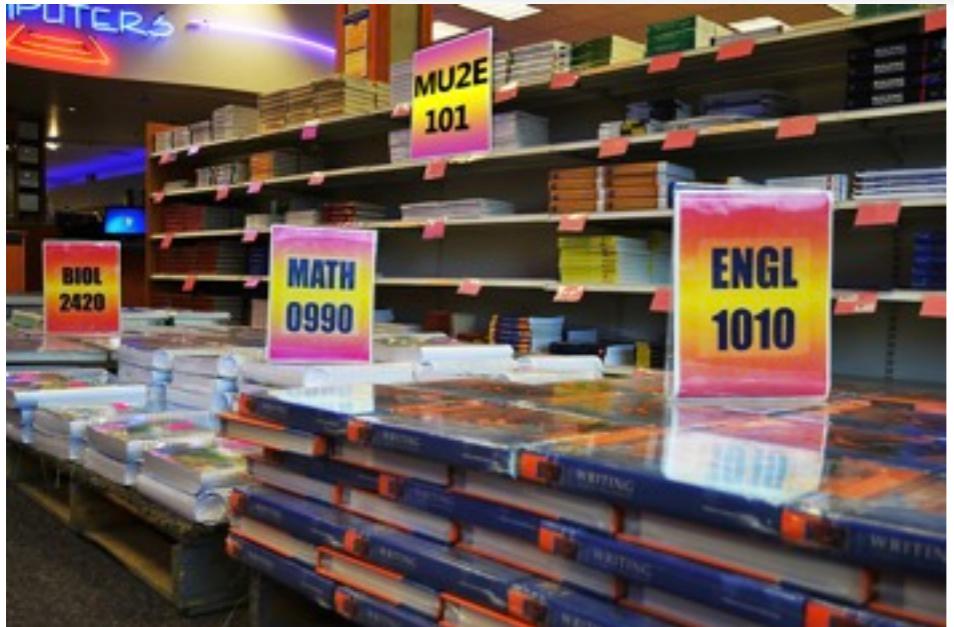
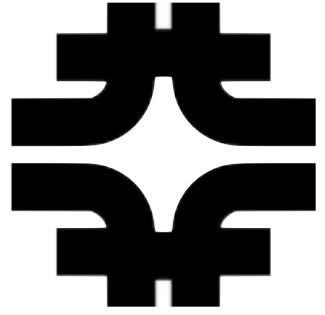


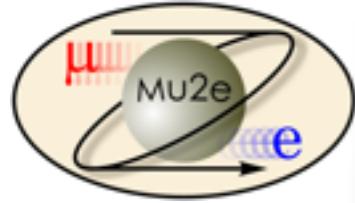
# A textbook mu2e experiment



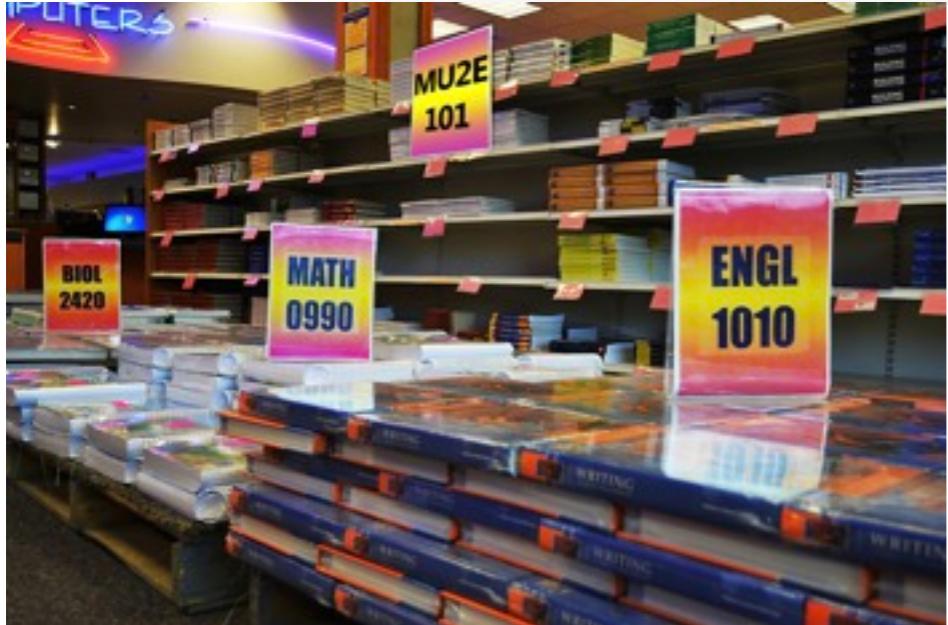
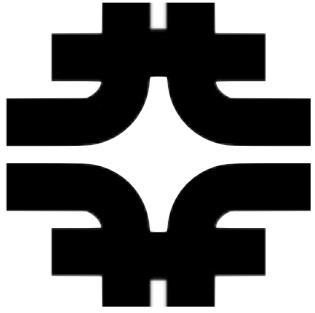


# A textbook mu2e experiment



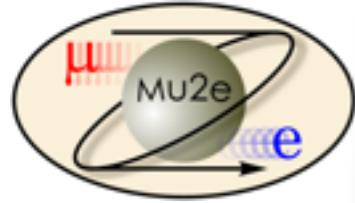


# A textbook mu2e experiment

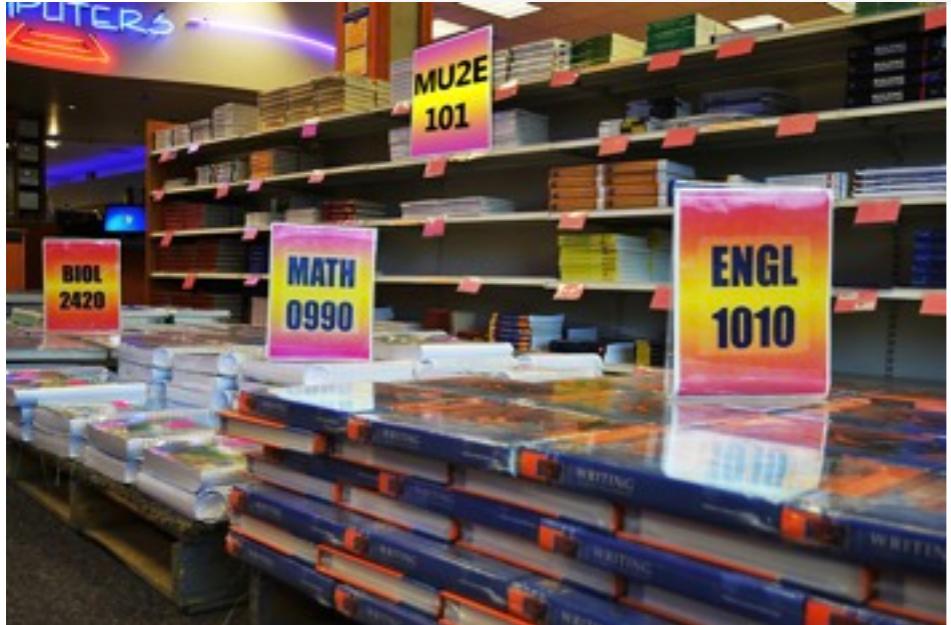
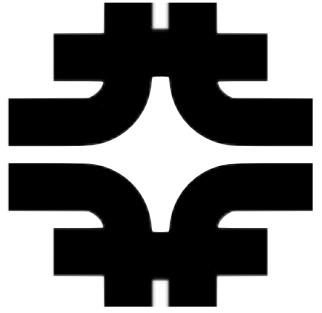


- Lots of muons
  - ◆ 50000000000/s
  - ◆ ×1000 compared to last
  - ◆ Total:  $5 \times 10^{19} \rightarrow 100 \times$  less than the number of grains of sand on Earth beaches

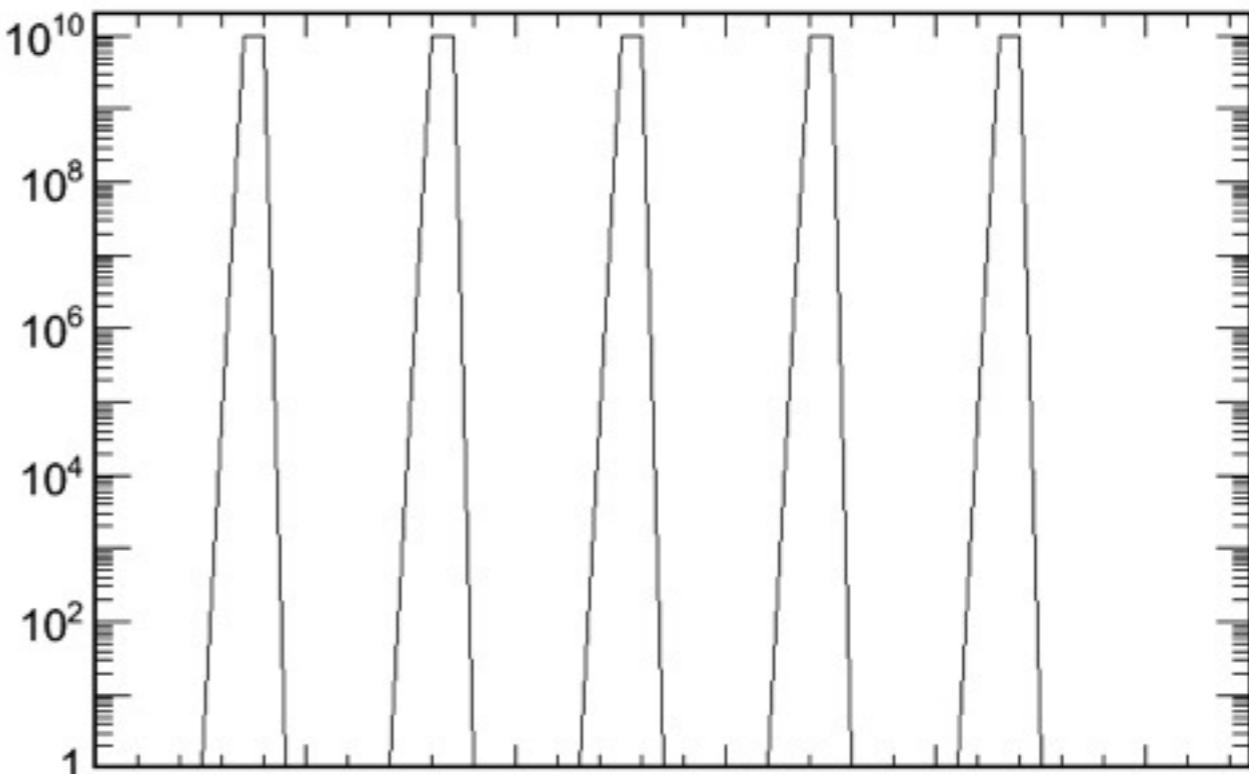


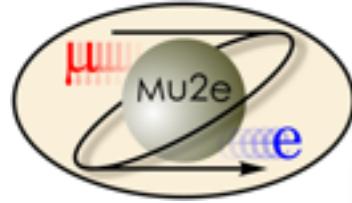


# A textbook mu2e experiment

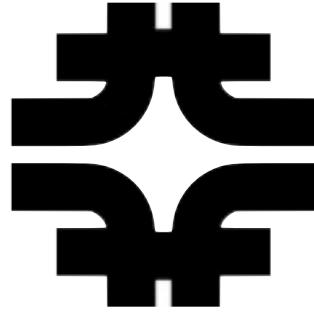


- Lots of muons
  - ◆  $50000000000/\text{s}$
  - ◆  $\times 1000$  compared to last
  - ◆ Total:  $5 \times 10^{19} \rightarrow 100 \times$  less than the number of grains of sand on Earth beaches
- No beam contamination
  - ◆  $< 10^{-10}$  out-of-pulse/in-pulse
  - ◆  $10^{-3} - 10^{-4}$  typical

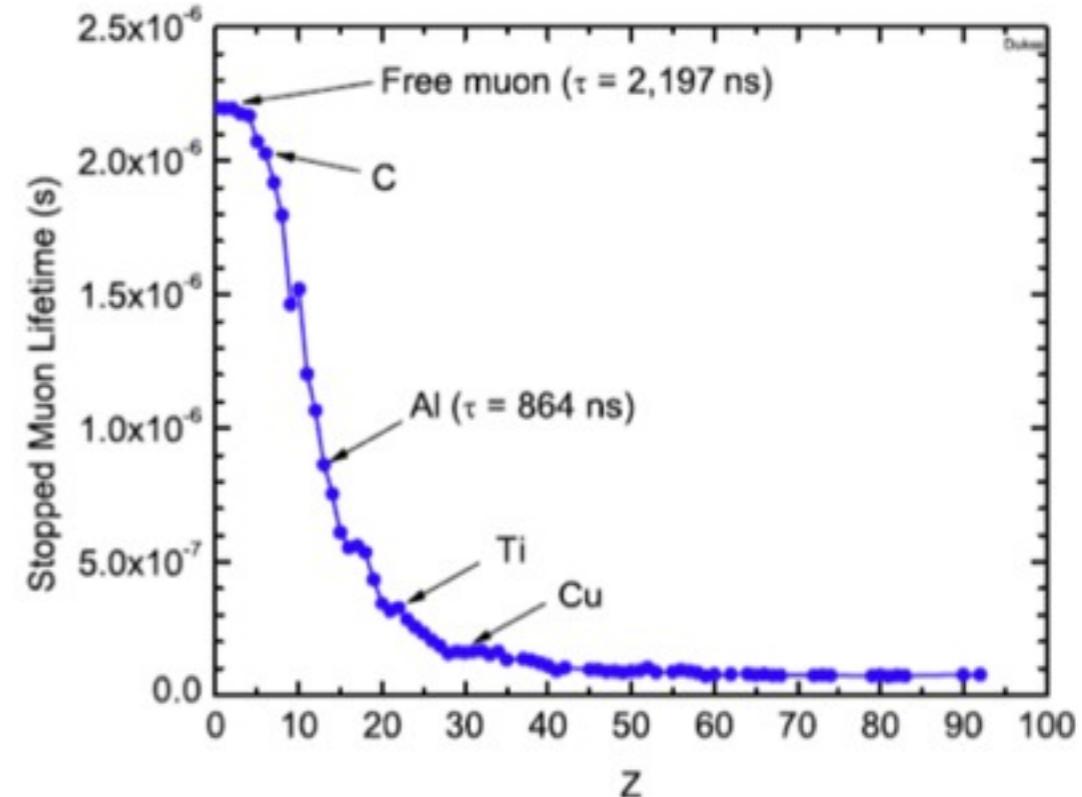
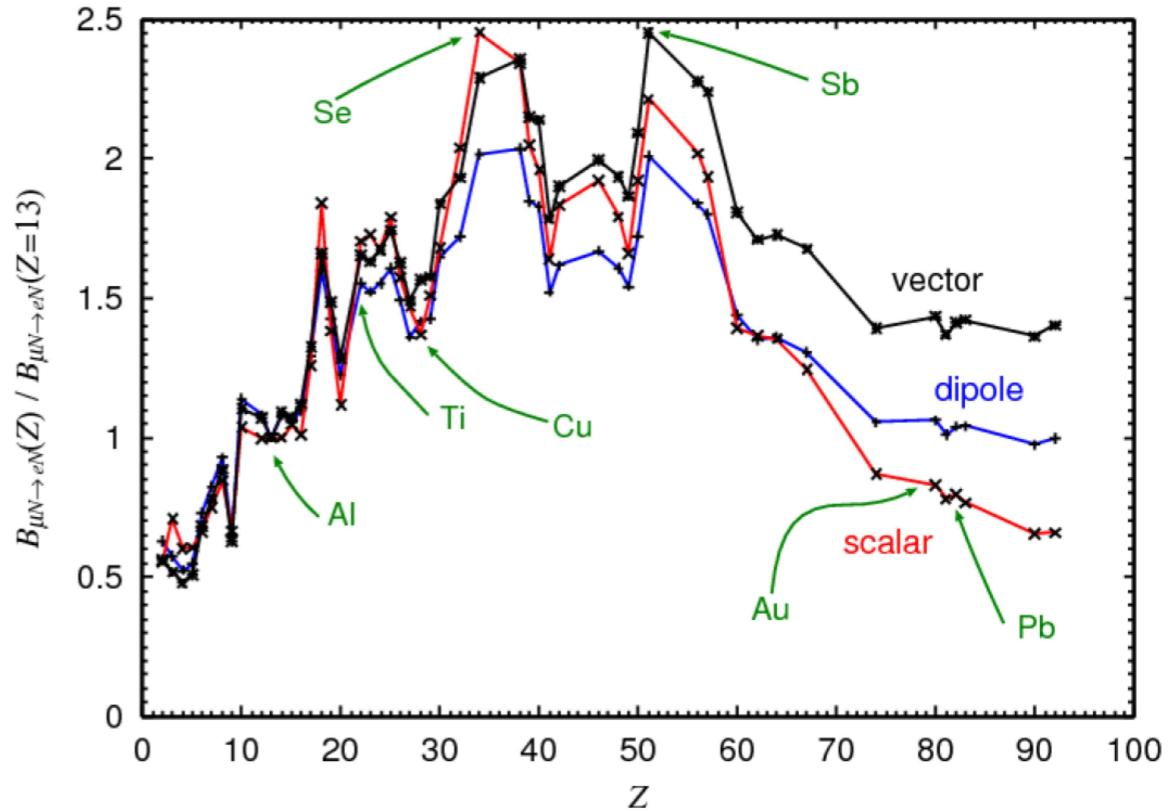


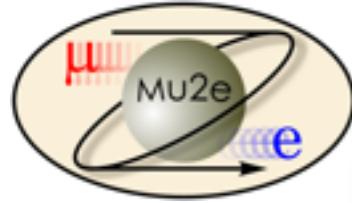


# A textbook mu2e experiment

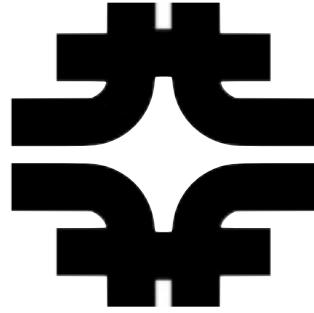


- Lots of muons
  - ◆ 50000000000/s
  - ◆ ×1000 compared to last
  - ◆ Total:  $5 \times 10^{19} \rightarrow 100 \times$  less than the number of grains of sand on Earth beaches
- No beam contamination
  - ◆  $< 10^{-10}$  out-of-pulse/in-pulse
  - ◆  $10^{-3} - 10^{-4}$  typical
- Target with high Z and long lifetime





# A textbook mu2e experiment

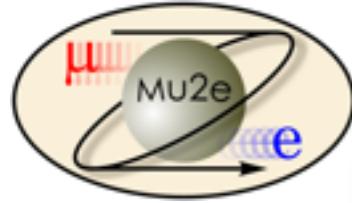


- Lots of muons
  - ◆ 50000000000/s
  - ◆  $\times 1000$  compared to last
  - ◆ Total:  $5 \times 10^{19} \rightarrow 100 \times$  less than the number of grains of sand on Earth beaches
- No beam contamination
  - ◆  $< 10^{-10}$  out-of-pulse/in-pulse
  - ◆  $10^{-3} - 10^{-4}$  typical
- Target with high Z and long lifetime
- Perfect resolution
  - ◆ spectrometer in vacuum with zero mass

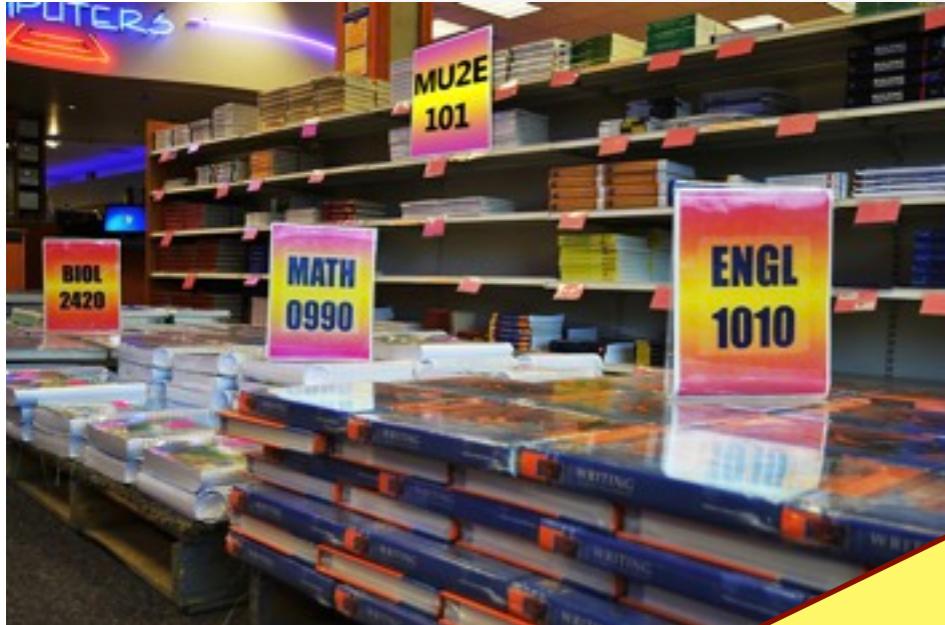
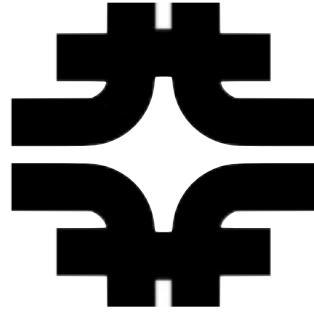
**ZERO MASS**  
THE NEXT GENERATION IN LIGHTWEIGHT FOOTWEAR.  
Designed with the highest quality lightweight components, the Zero Mass Collection allows for natural movement and lasting comfort.

[WATCH VIDEO](#)





# A textbook mu2e experiment



- Lots of muons
  - ◆ 500000000
  - ◆  $\times 1000$
  - ◆ Total: 5x of grains of sand
- No beam control
  - ◆  $<10^{-10}$  out-of-plane
  - ◆  $10^{-3} - 10^{-4}$  typically
- Target with high Z and long lifetime
- Perfect resolution
  - ◆ spectrometer in vacuum with zero mass

maybe is time to look at etomu?  
Too hard!!!!

ZERO MASS

NEXT GENERATION  
IN LIGHTWEIGHT FOOTWEAR.

Designed with the highest quality lightweight components, the Zero Mass Collection allows for natural movement and lasting comfort.

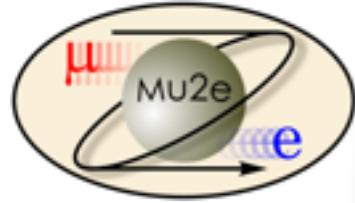
WATCH VIDEO

WOLVERINE®  
**Warrior**  
LEATHER

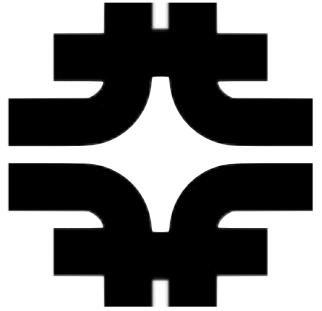
STAIN-RESISTANT LEATHER

ZERO MASS TECHNOLOGY

WHAT'S INSIDE?



# mu2e collaboration



Boston University

Brookhaven National Laboratory

University of California, Berkeley

University of California, Irvine

California Institute of Technology

City University of New York

Duke University

Fermilab

University of Houston

University of Illinois, Urbana-Champaign

University of Massachusetts, Amherst

Lawrence Berkeley National Laboratory

Northern Illinois University

Northwestern University

Pacific Northwest National Laboratory

Rice University

University of Virginia

University of Washington, Seattle



Istituto G. Marconi Roma

Laboratori Nazionali di Frascati

Università di Pisa, Pisa

INFN Lecce and Università del Salento

Gruppo Collegato di Udine

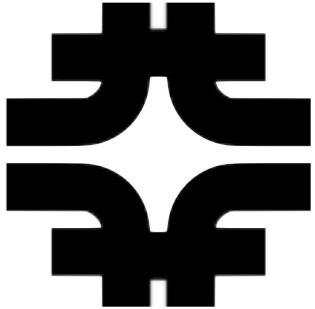
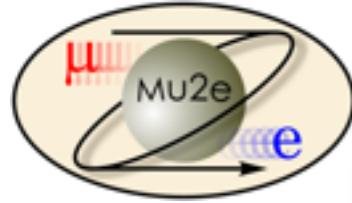


Institute for Nuclear

Research, Moscow, Russia

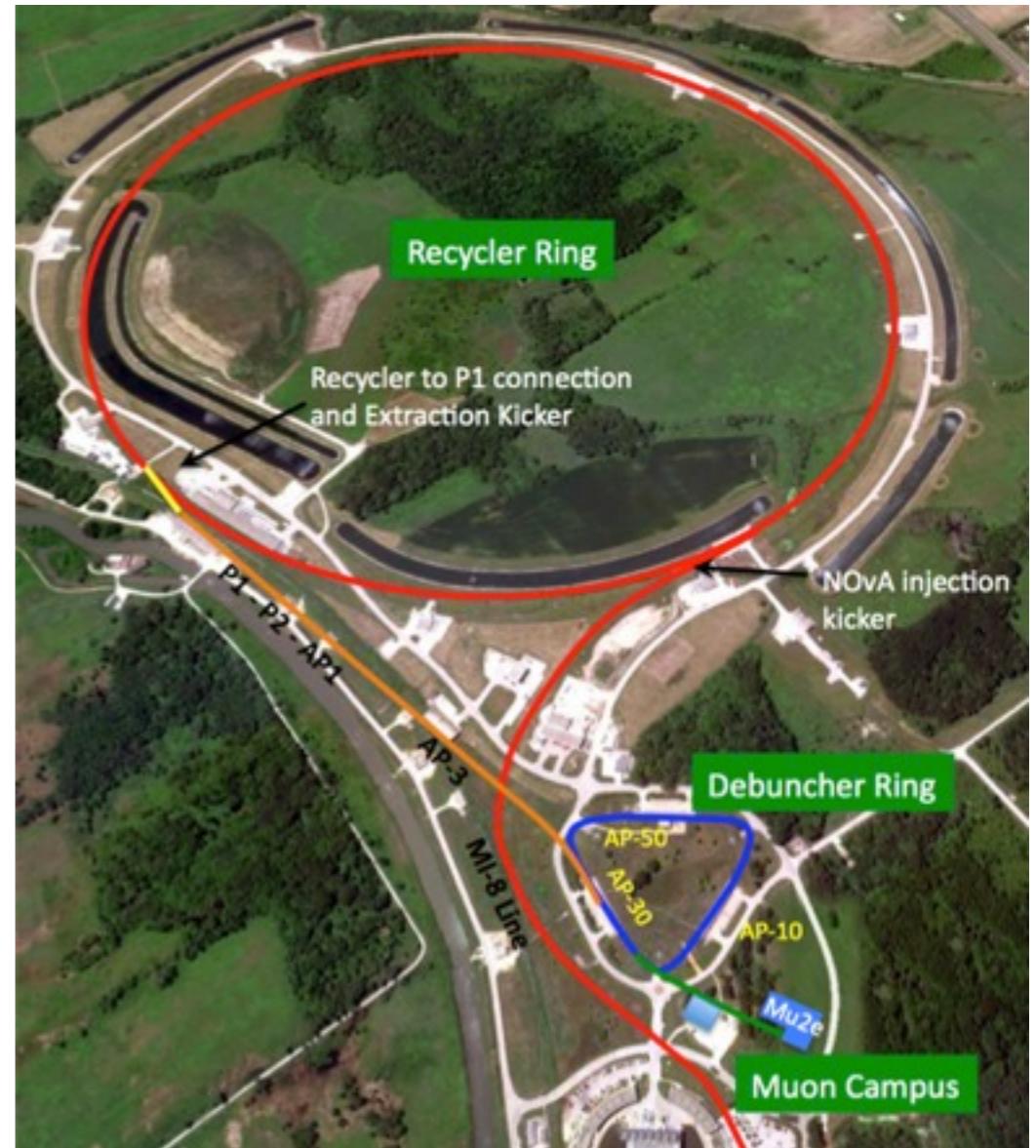
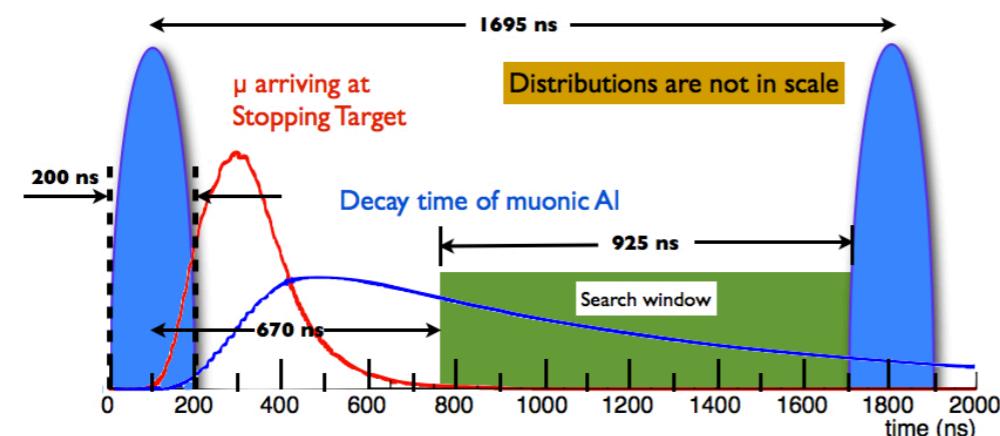
JINR, Dubna, Russia

~130 collaborators

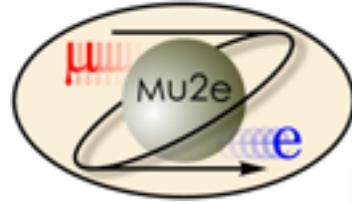


# Fermilab complex

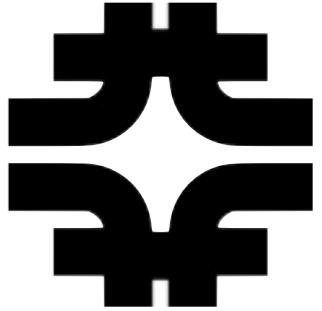
- Booster:  $4 \times 10^{12}$  p/batch every 1/15s
  - ◆ Nova: 12 stacked in the Recycler and then to MI
  - ◆ MI cycle 1.33s
  - ◆ 8 batches available
- 2 used by mu2e
  - ◆ Recycler RF manipulation into 4 bunches ~200ns each
  - ◆ Transfer to Debuncher
- Debuncher period  $1.7\mu\text{s}$ 
  - ◆ Resonant extraction from Debuncher → beam to muon production target



- $6 \times 10^{12}$  p/s delivered to muon production
  - $3.1 \times 10^7$  protons/bunch



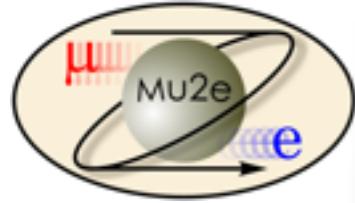
# Fermilab muon campus



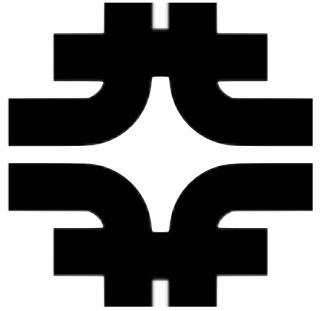
Reuse as much as possible the current collider complex



- Small changes to the existing antiproton rings
- Allow mu2e and g-2 this decade (8GeV muon program)
- No interference with the 120GeV neutrino program (Nova)

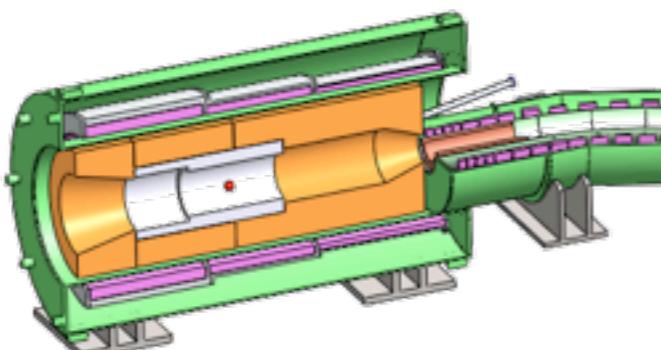


# Experiment

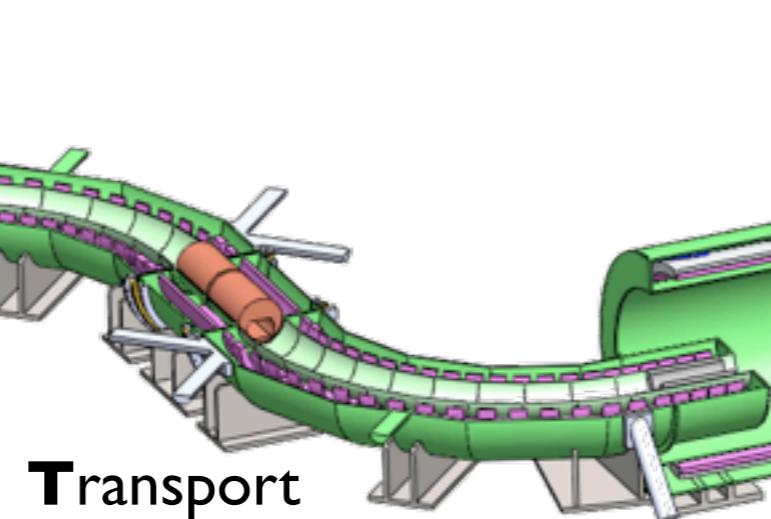


- $\pi$  from p in PS -  $\pi \rightarrow \mu\nu$
- $\mu$ 's spiral down in S shape solenoid (TS)
- $\mu$ 's end on the conversion target in DS

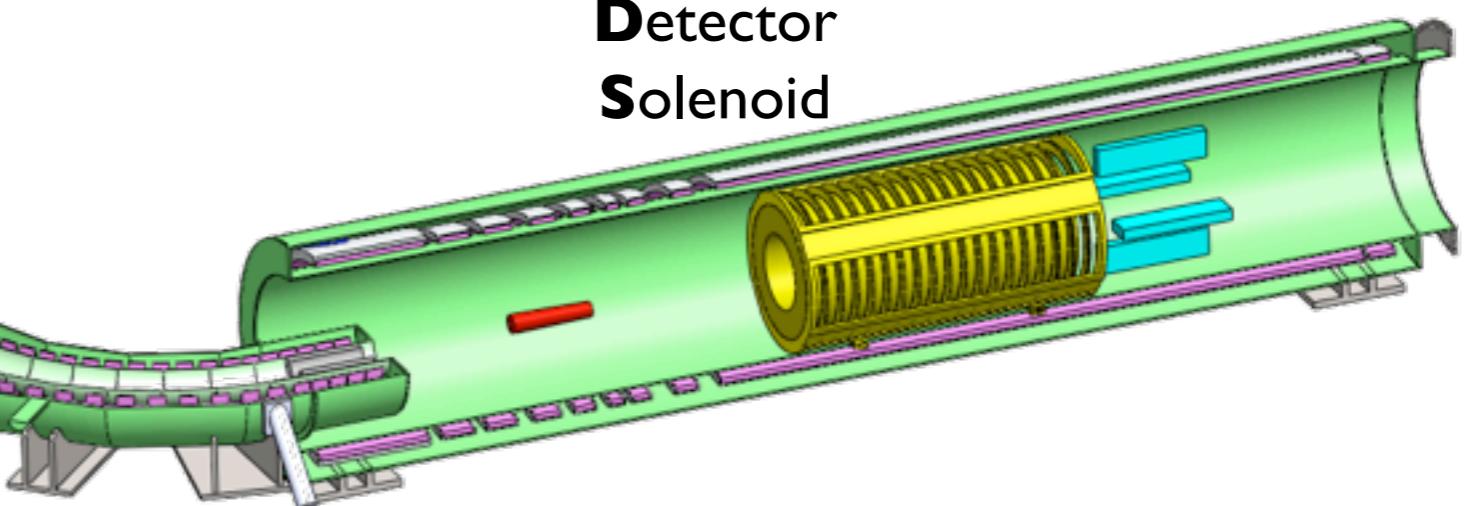
**Production  
Solenoid**



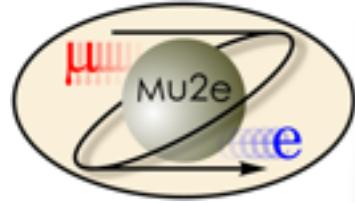
**Transport  
Solenoid**



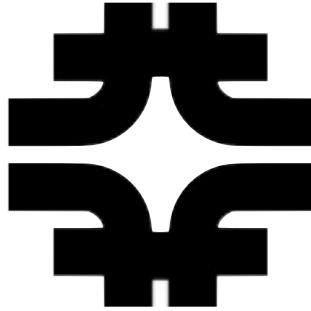
**Detector  
Solenoid**



$10^{-4}$  Torr vacuum  
throughout



# Production



Protons leave through  
thin window (extinction  
measurement after)

**4.6 T**

Proton Target  
(W rod  $160 \times 3$  mm)

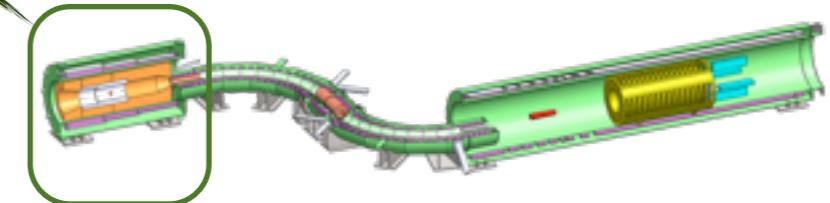
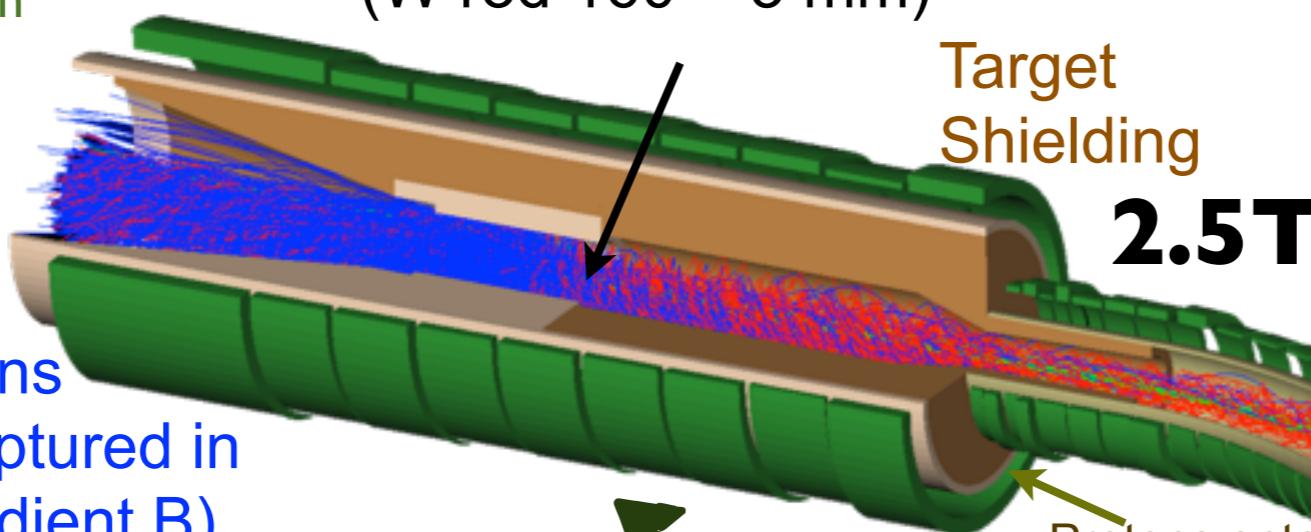
Target  
Shielding

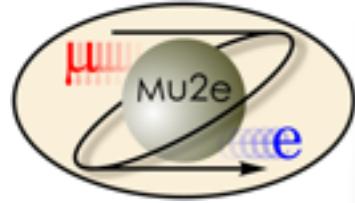
**2.5 T**

Pions  
(captured in  
gradient B)

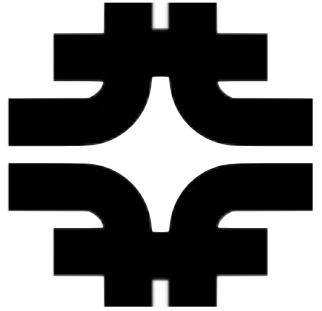
Protons enter here  
(opposite to outgoing  $\mu$ 's)

→ **4m × 0.3m** ←

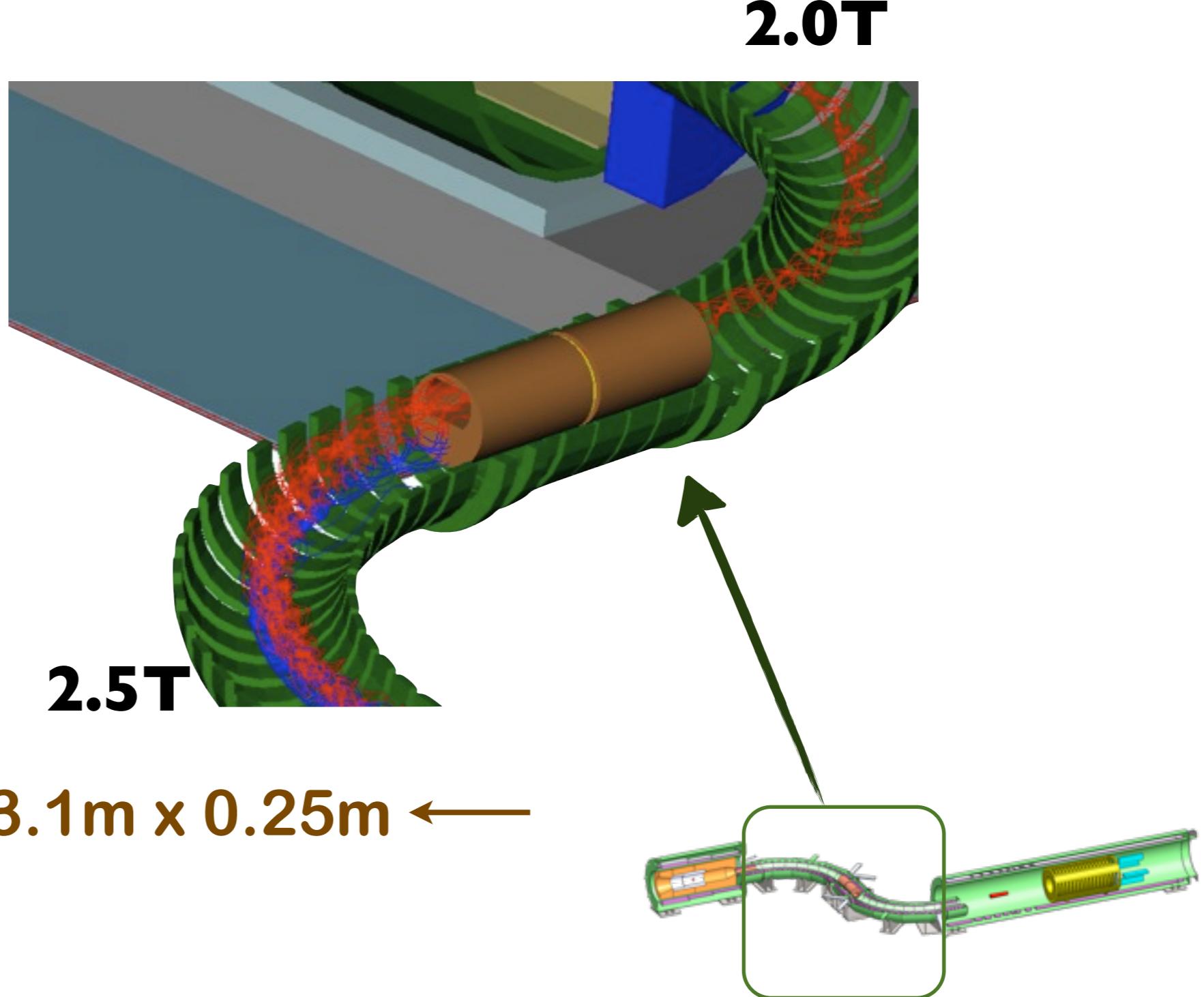


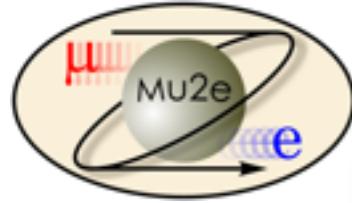


# Transport

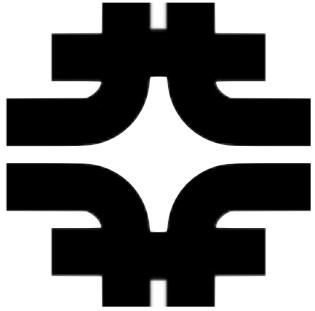


- Curved solenoid eliminates line of sight
  - ◆ No neutrals transport
- Sign selection
  - ◆ S shape solenoid + collimator





# Detection

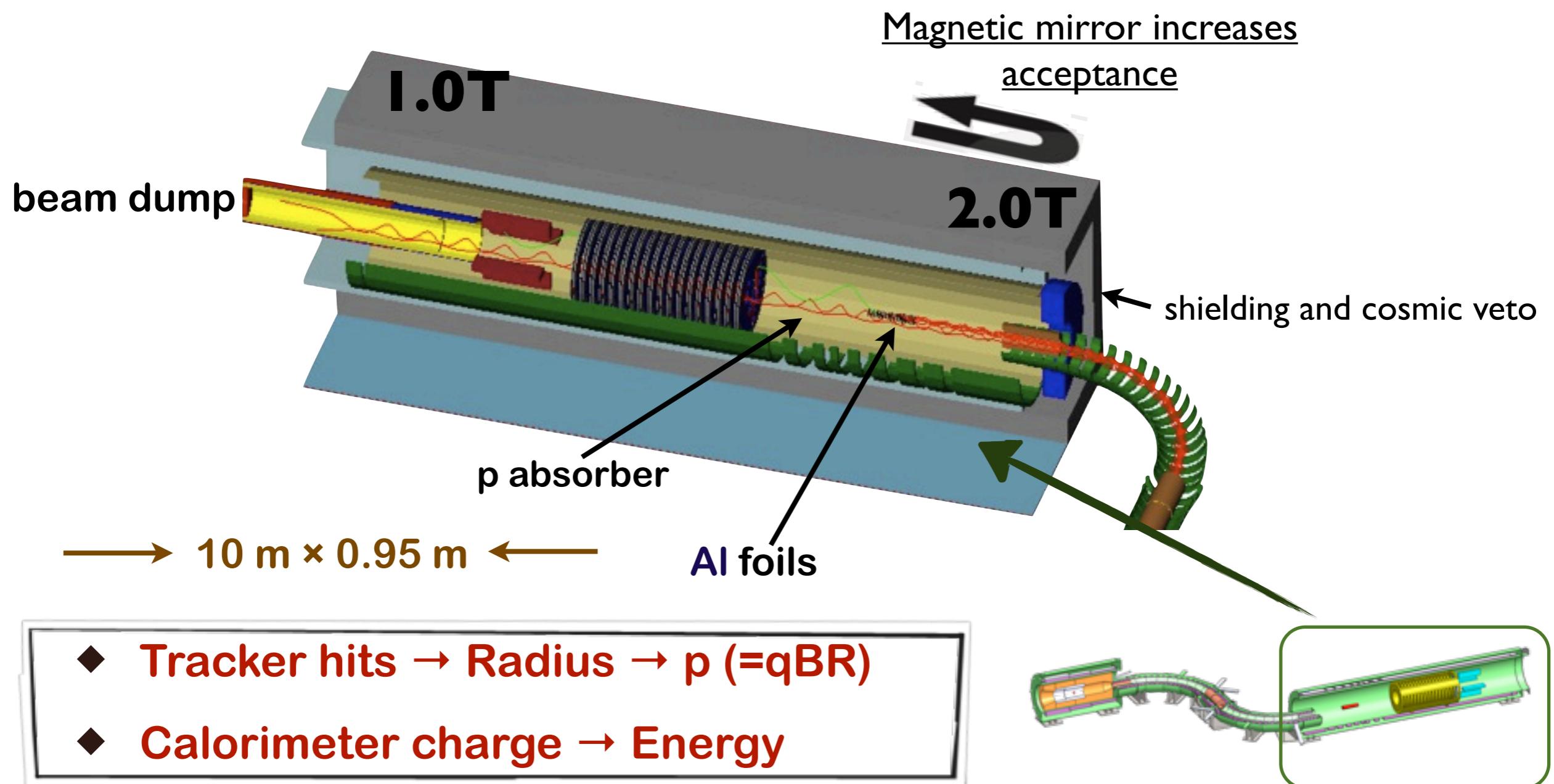


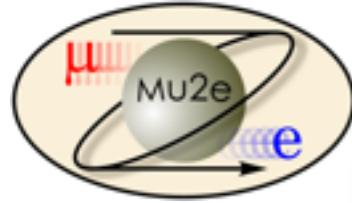
- **Calorimeter**

- ◆ ~1024  $3.5 \times 3.5 \times 12$  cm  
PbWO<sub>4</sub> or LYSO
- ◆ 2% resolution

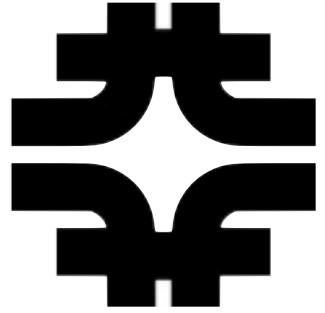
- **Tracker**

- ◆ Transverse geometry
- ◆ 21600 straws
- ◆ 18 stations

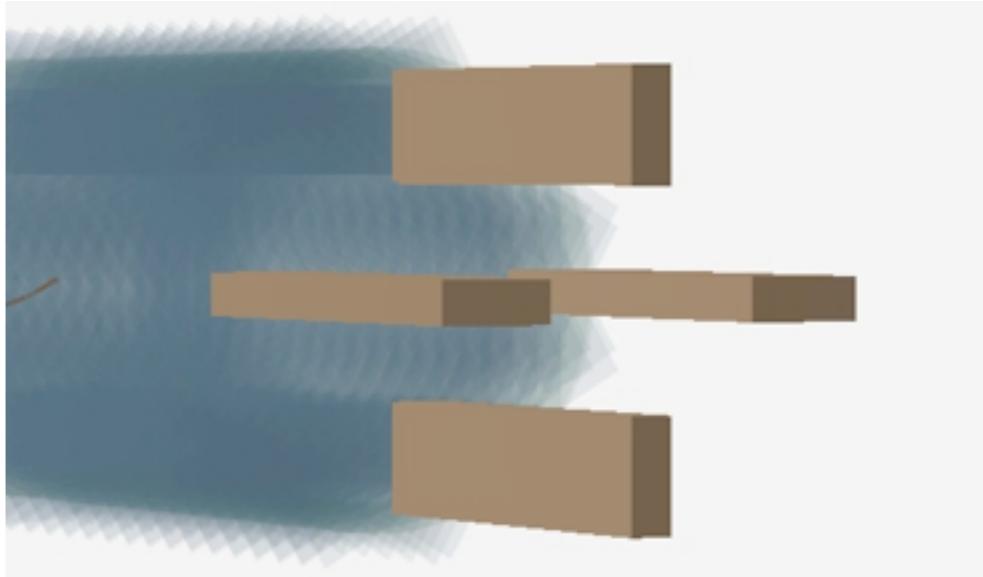




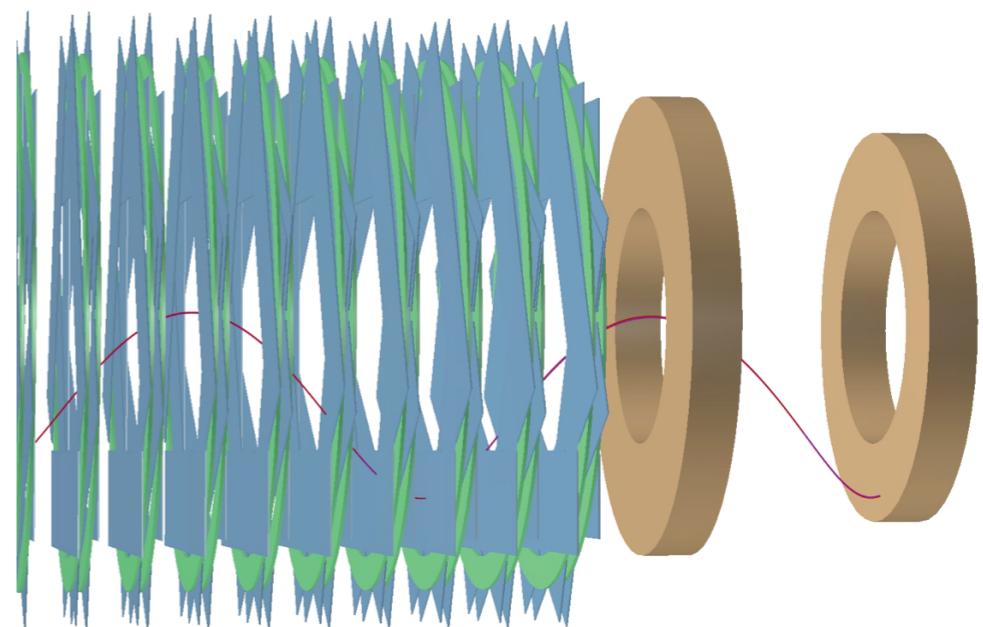
# mu2e calorimeter

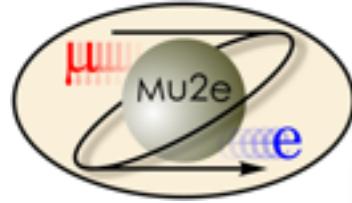


- Vane (baseline)
  - ◆ electron tracks spiral into flat faces
  - ◆ neutrons from stopping target hit edge
- Disk (new idea)
  - ◆ facing neutrons, so potentially more accidental activity worsening resolution
  - ◆ charge-symmetric!

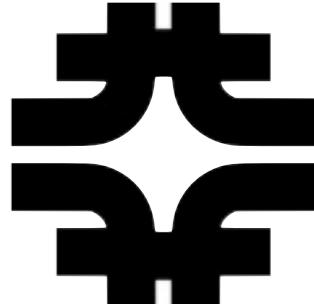


Two discs are separated by ~1/2 "wavelength"

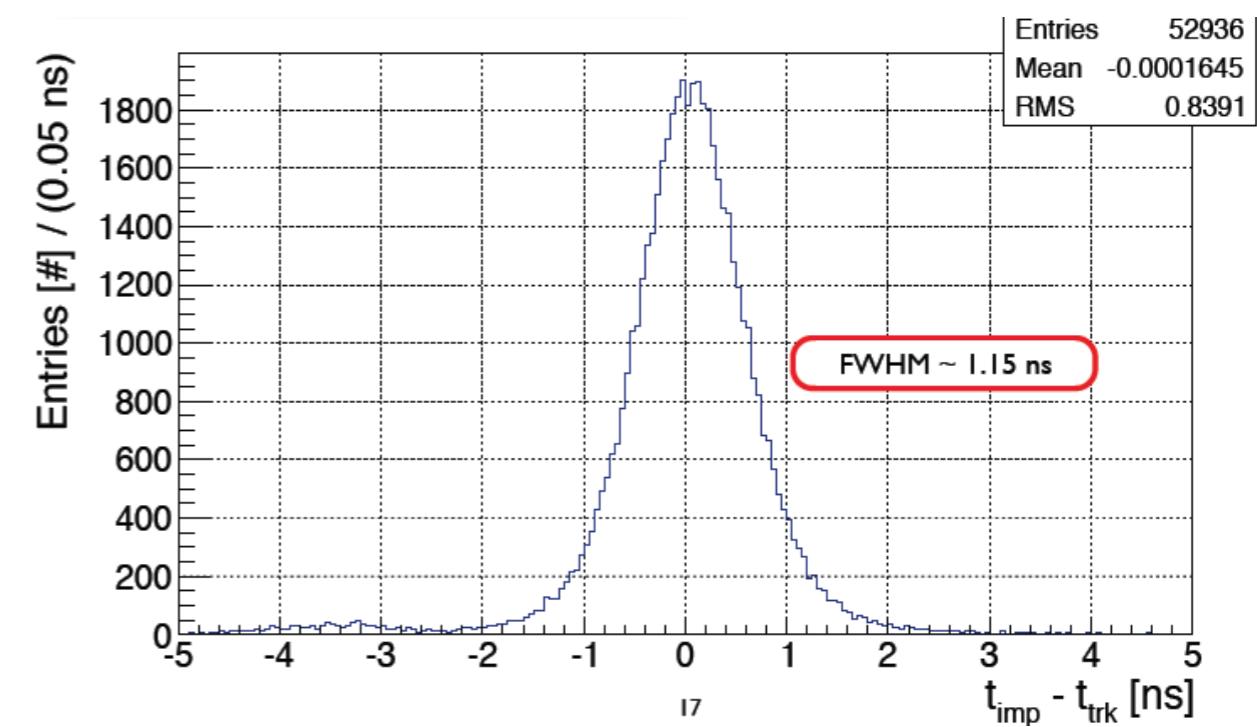
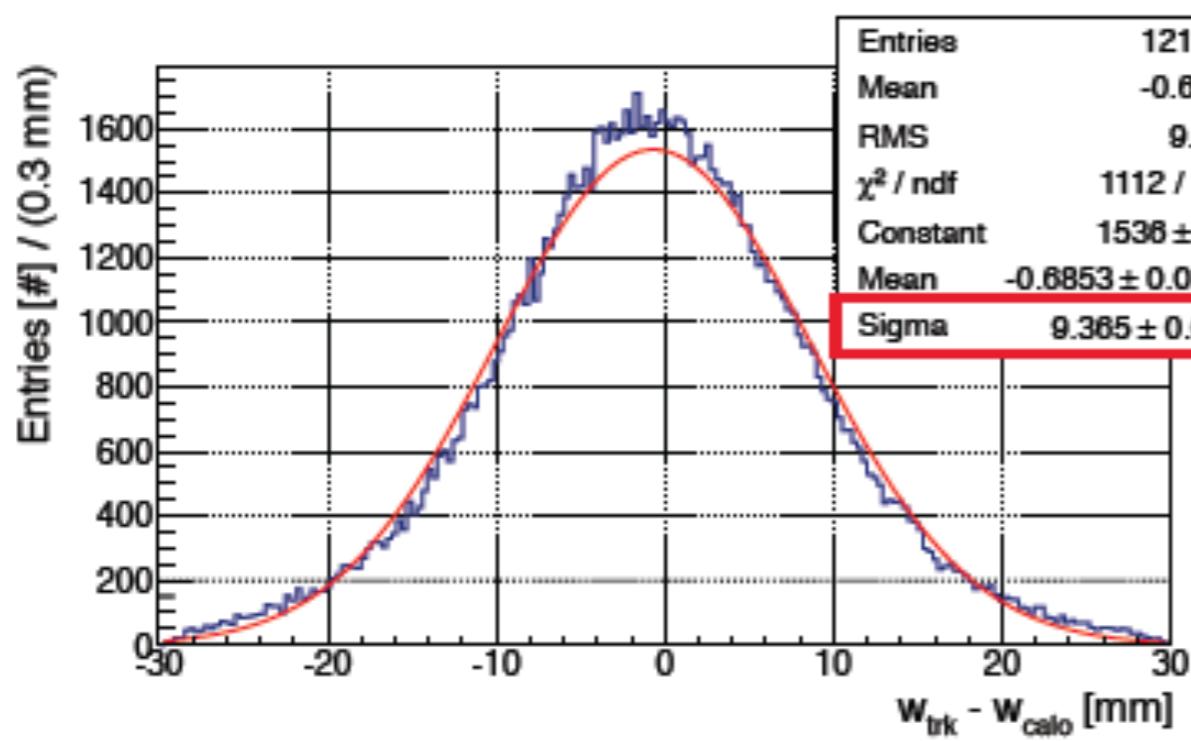
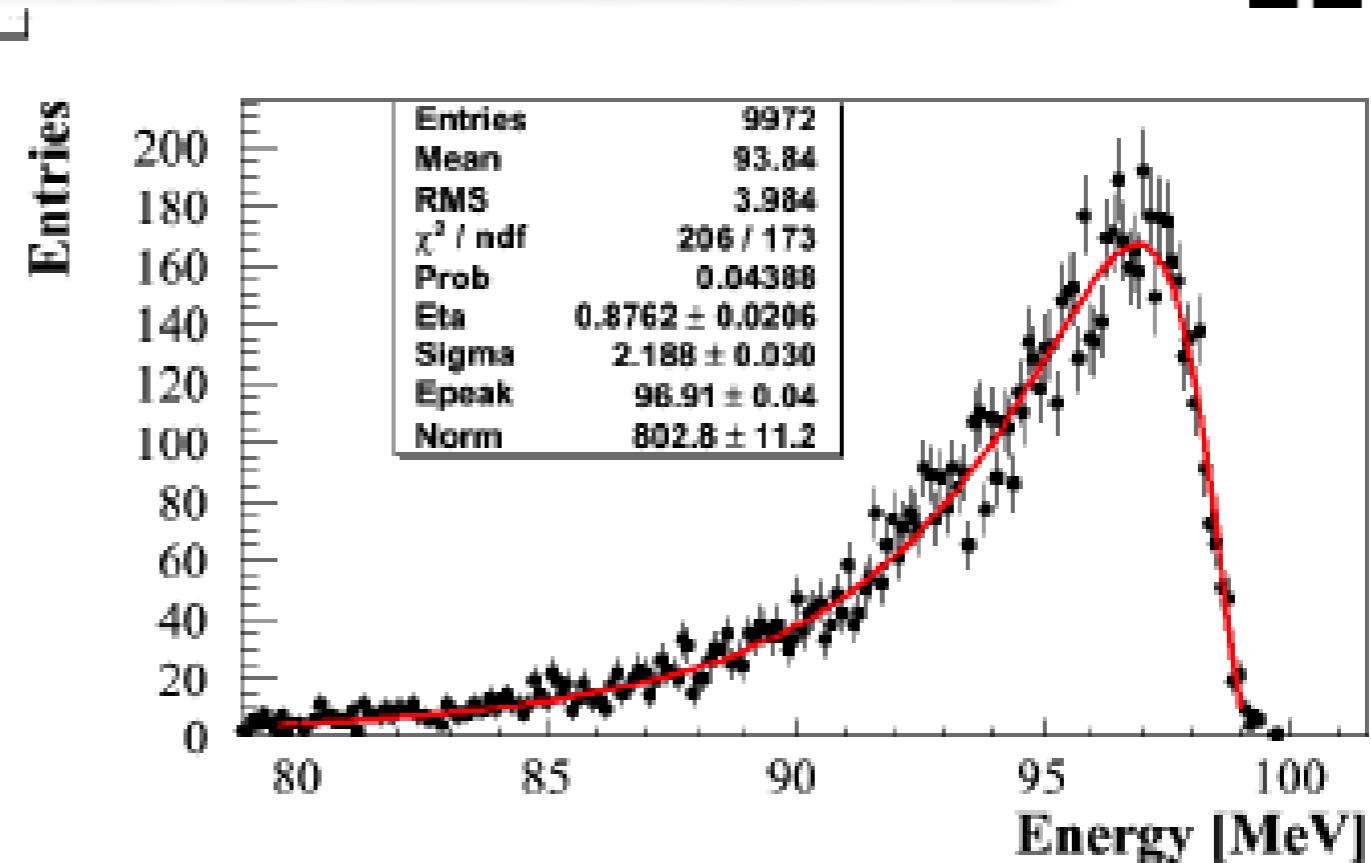


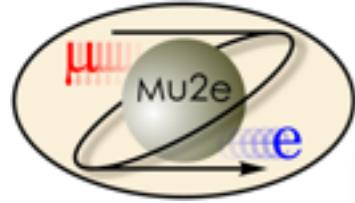


# mu2e calorimeter

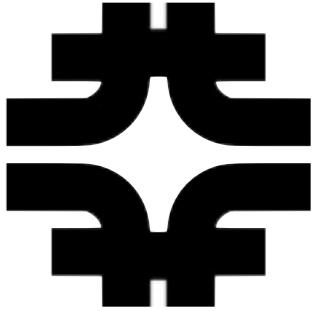


- Trigger the detector
- Confirm the track
- Separate measurement



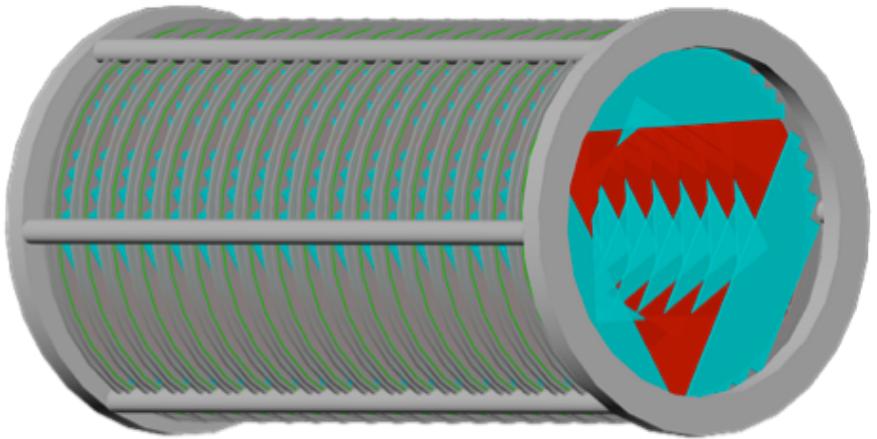


# mu2e Tracker

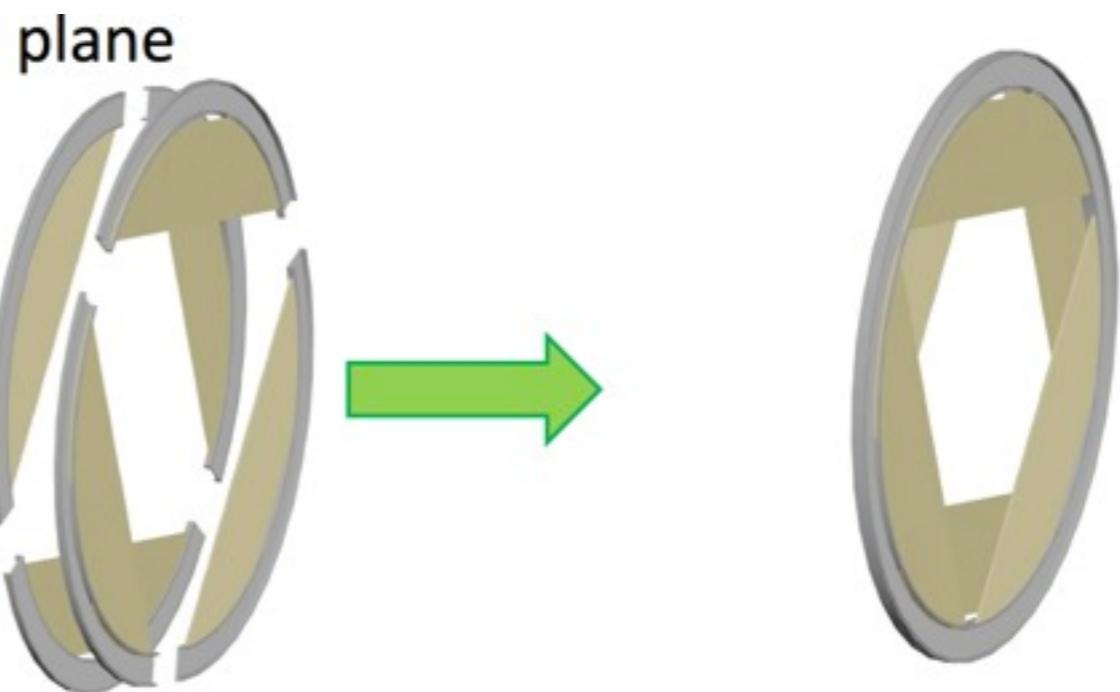


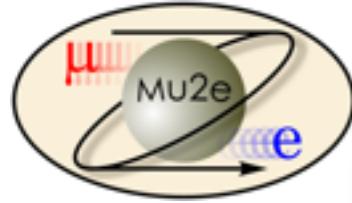
- **Tracker**

- ◆ 21600 straws in vacuum
  - ~39 hits/track
  - <0.25 X<sub>0</sub> for a typical track
- ◆ Electronics at straw end
- ◆ All support at large radius

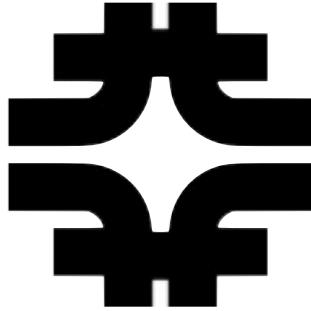


- Self supporting panels assembled into planes
- Planes assembled into stations
- Rotating 60° for improved stereo



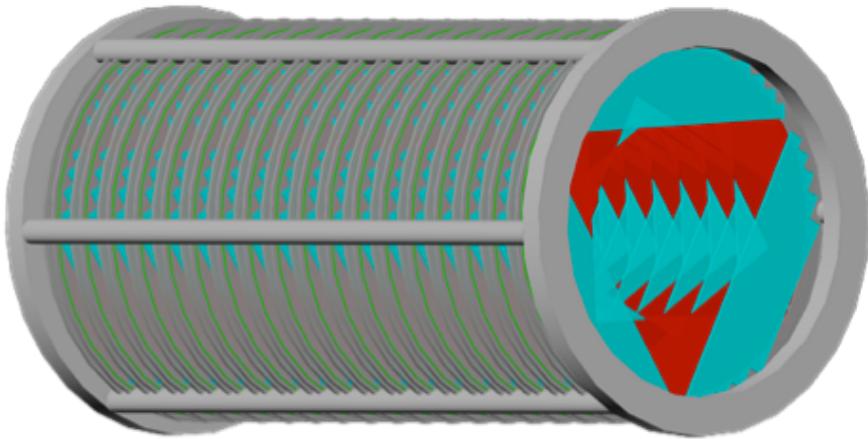


# mu2e Tracker

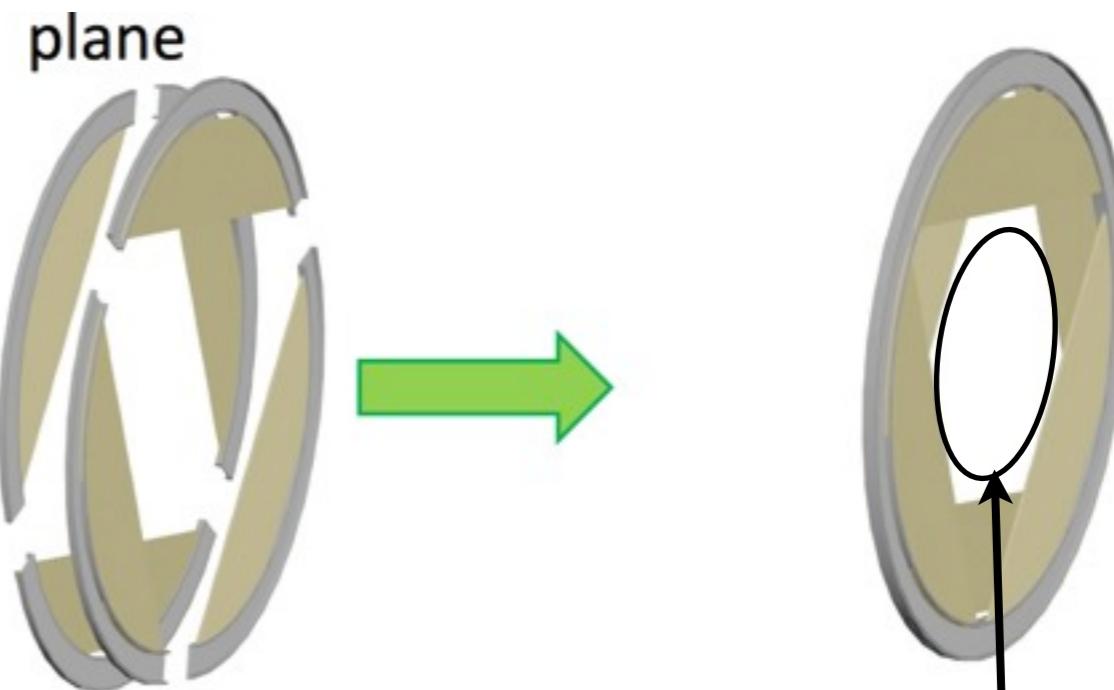


- **Tracker**

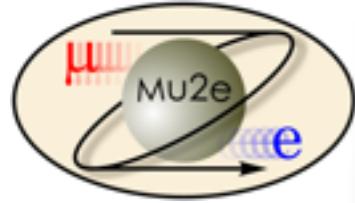
- ◆ 21600 straws in vacuum
  - ~39 hits/track
  - <0.25 X0 for a typical track
- ◆ Electronics at straw end
- ◆ All support at large radius



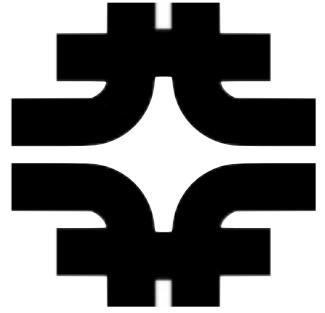
- Self supporting panels assembled into planes
- Planes assembled into stations
- Rotating 60° for improved stereo



Tracking at high radius  
only ensures operability  
(beam flash!)



# mu2e straw



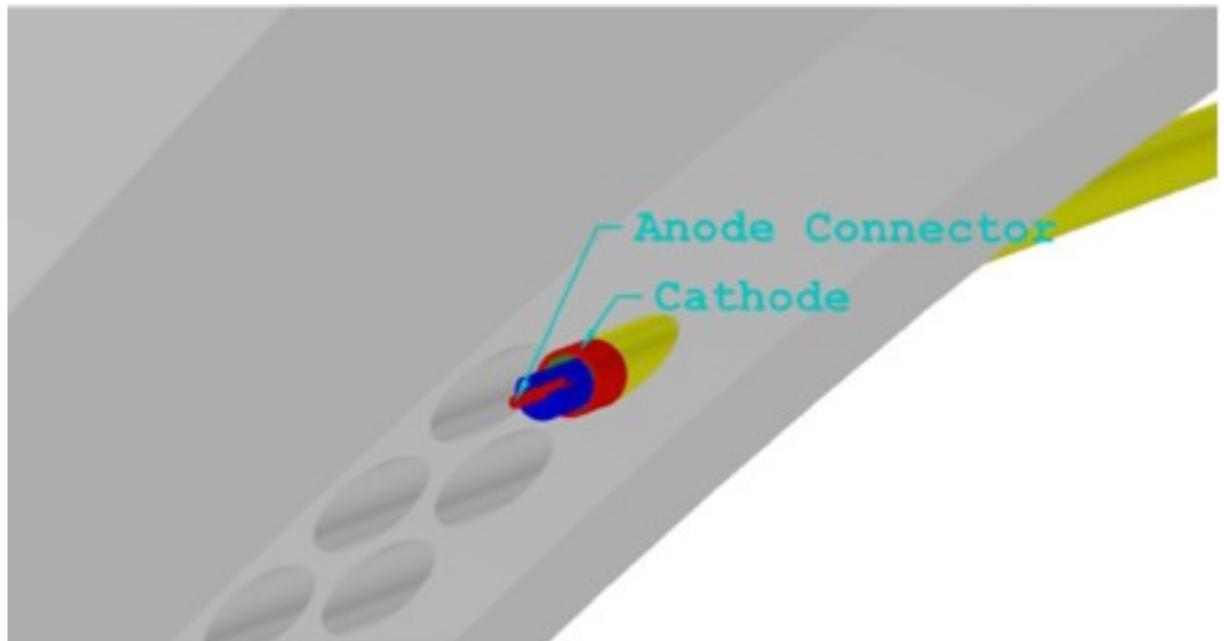
## ○ 15 microns Mylar

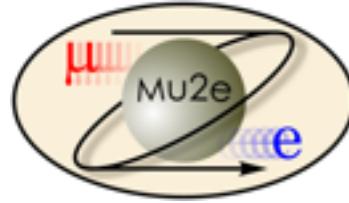
- ◆ 2x6.25 $\mu\text{m}$  Mylar spiral wound
- ◆ 500 $\text{\AA}$  Al
- ◆ 200 $\text{\AA}$  Au on inner surface



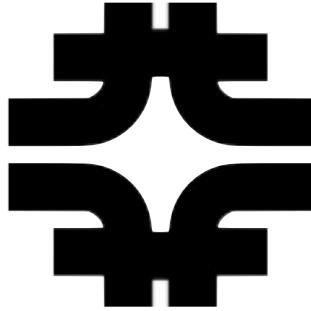
## ○ 5mm diameter straws

- ◆ 25  $\mu\text{m}$  W sense wire (Au covered)
- ◆ 334-1174 mm in length
- ◆ ArCO<sub>2</sub> (80/20) at HV<1500



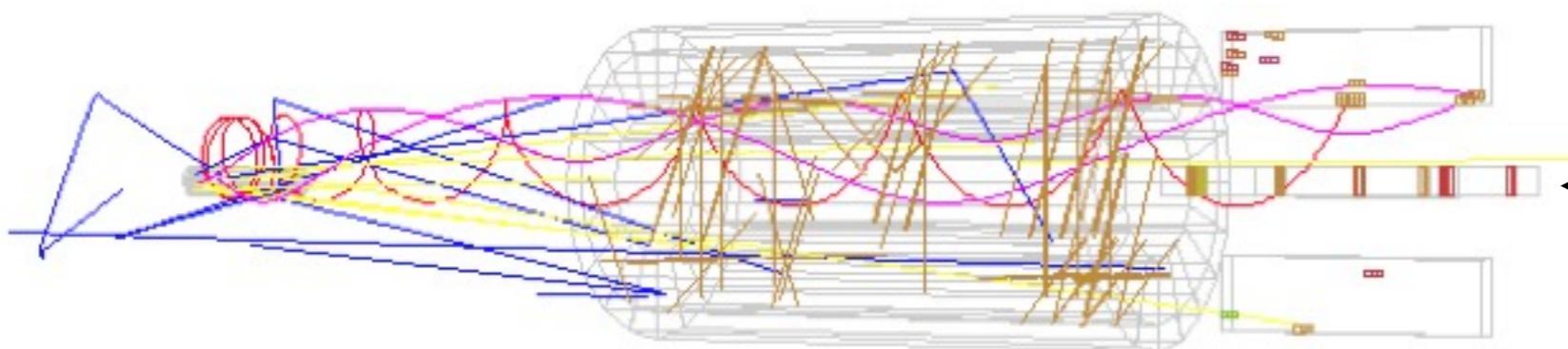
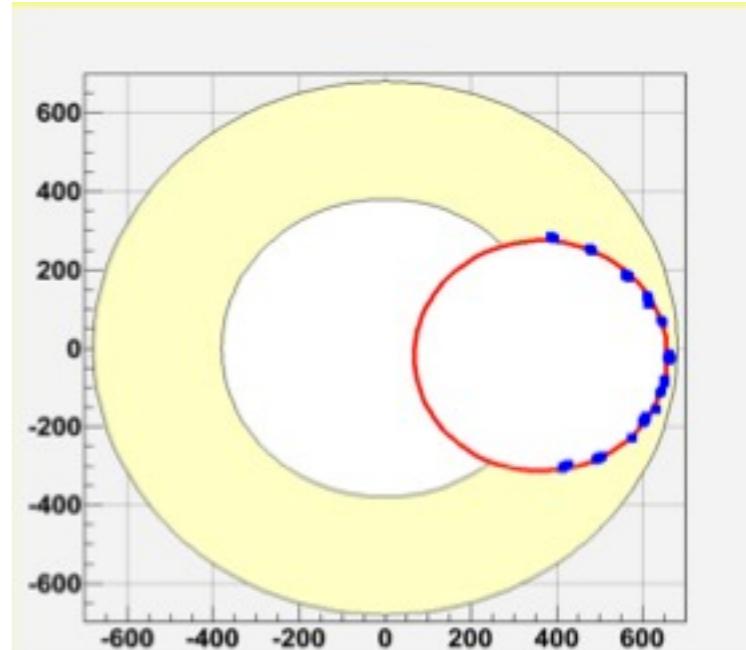
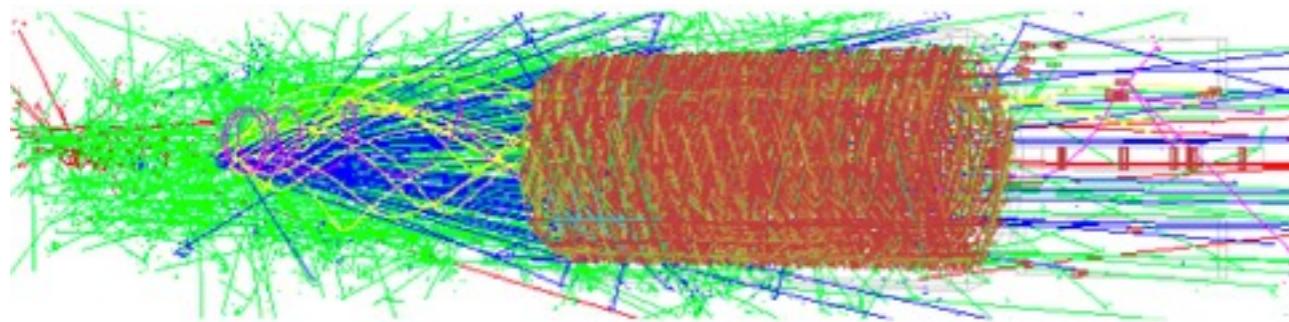


# A mu2e event



- Single proton pulse

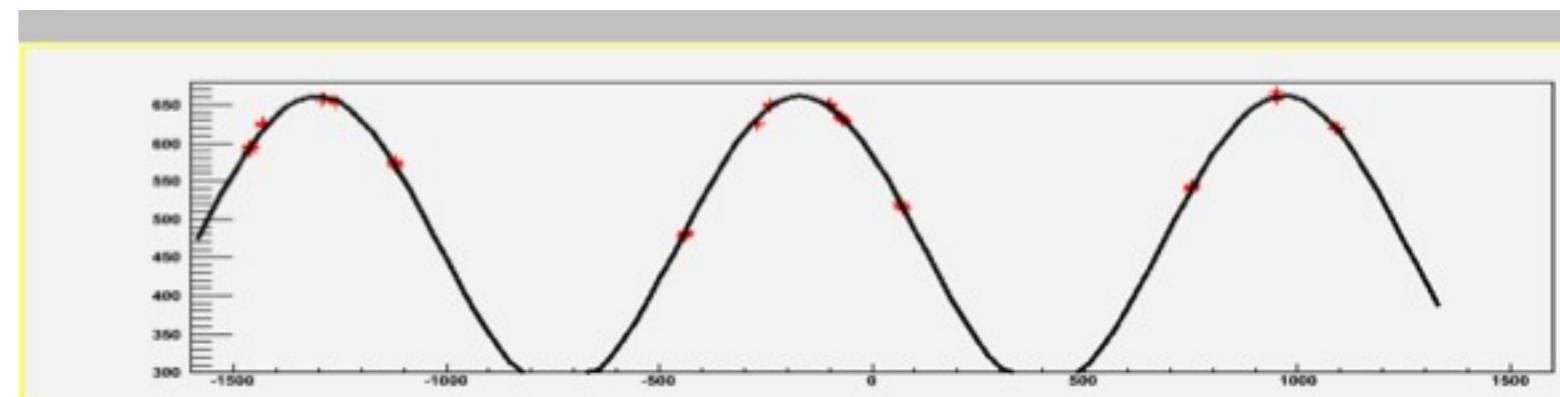
- ◆ particle hits in 500-1695ns window

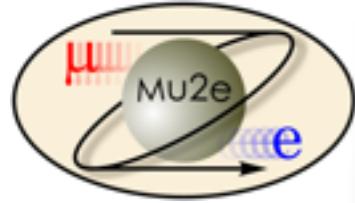


good timing helps  
( $\pm 50$  ns around C.E.)

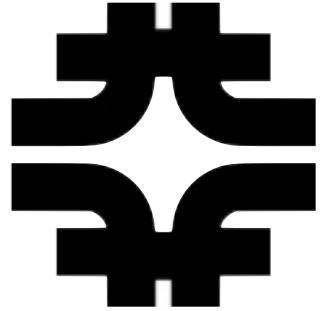
- Problem: find the red track

- Pattern recognition very hard



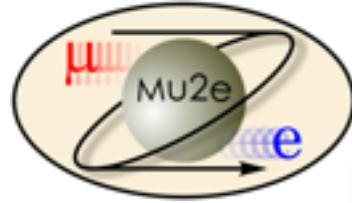


# Measuring the 3'rd coordinate

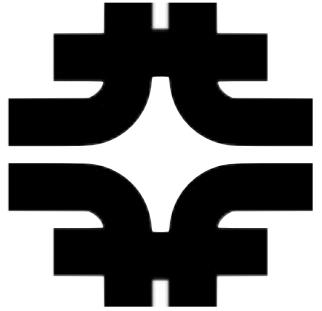


- z along the straw
  - ◆ obtained at high precision after the fit (stereo)
  - ◆ Crucial for pattern recognition
- Time division (read both ends of the straw)

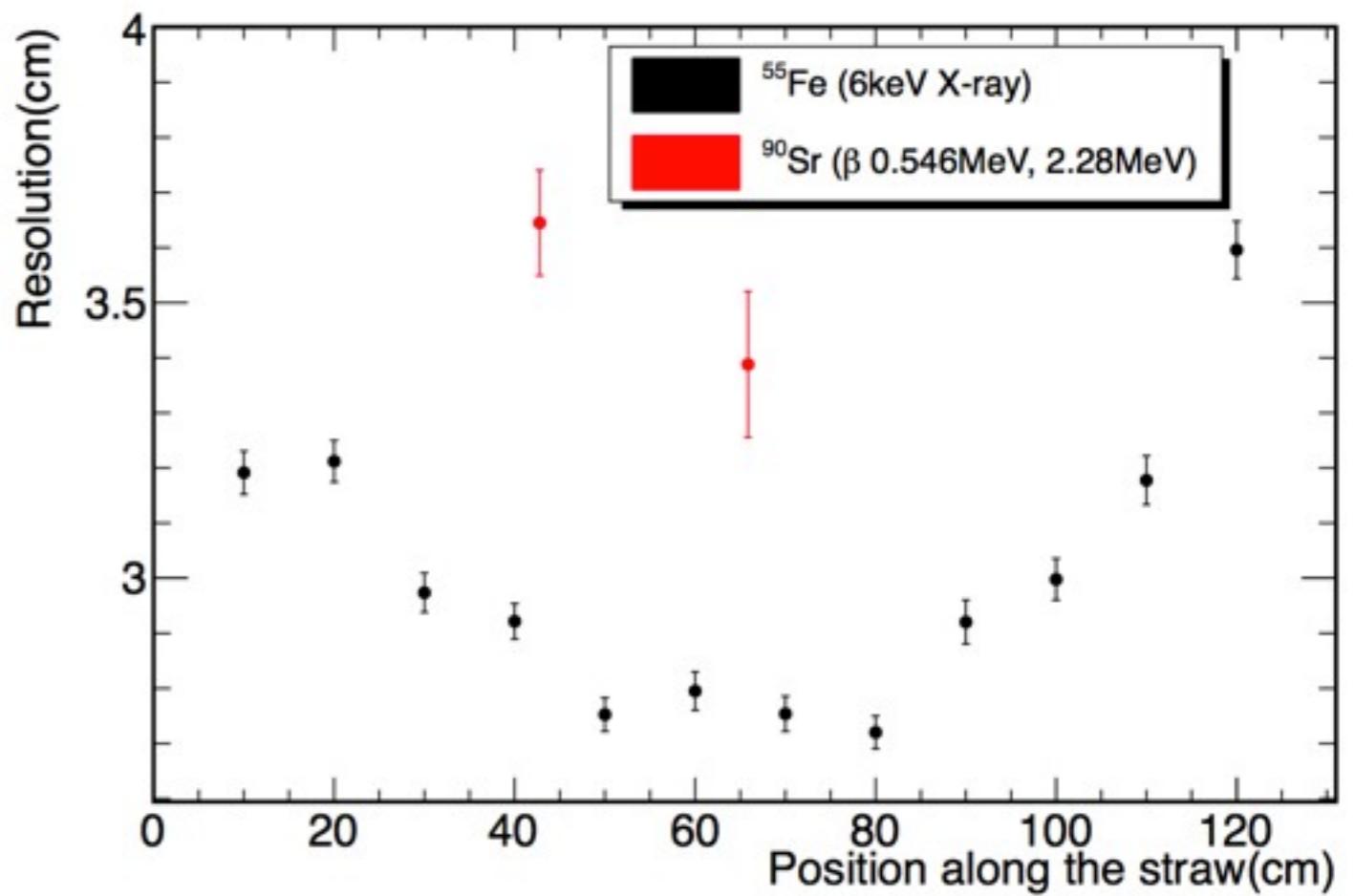
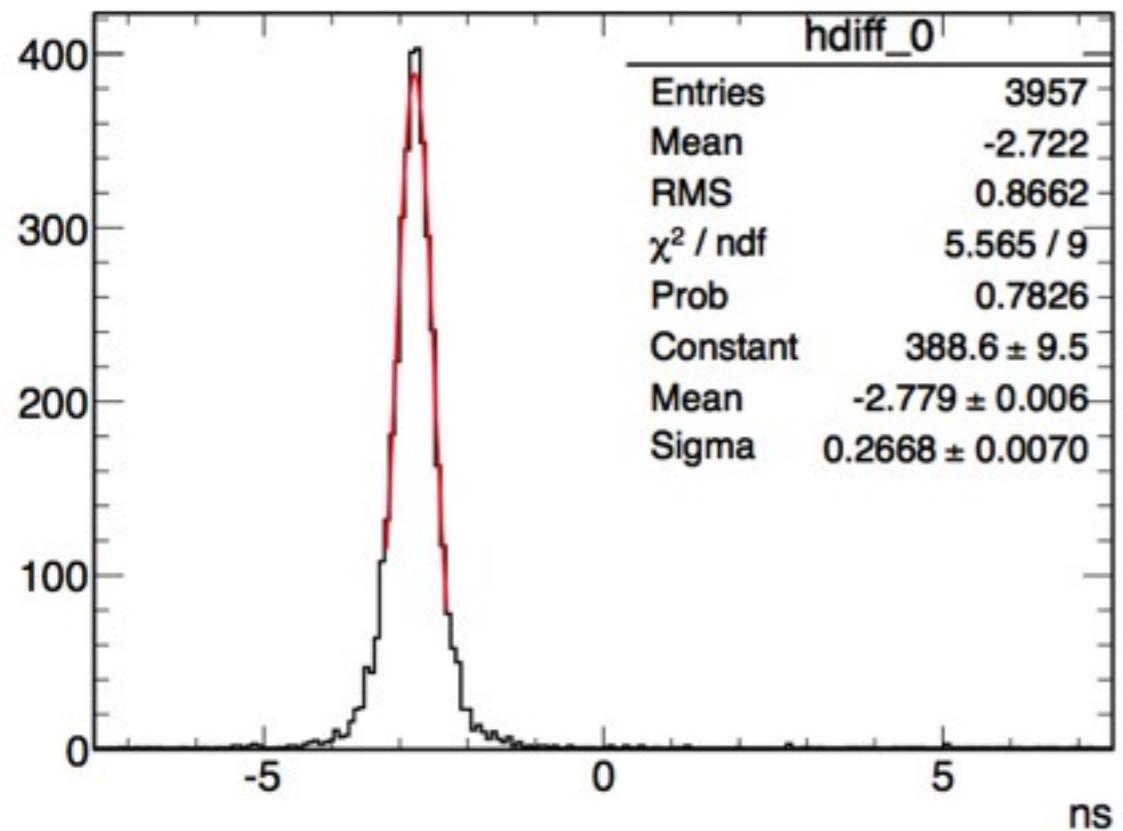


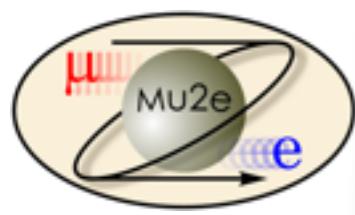


# Time Division

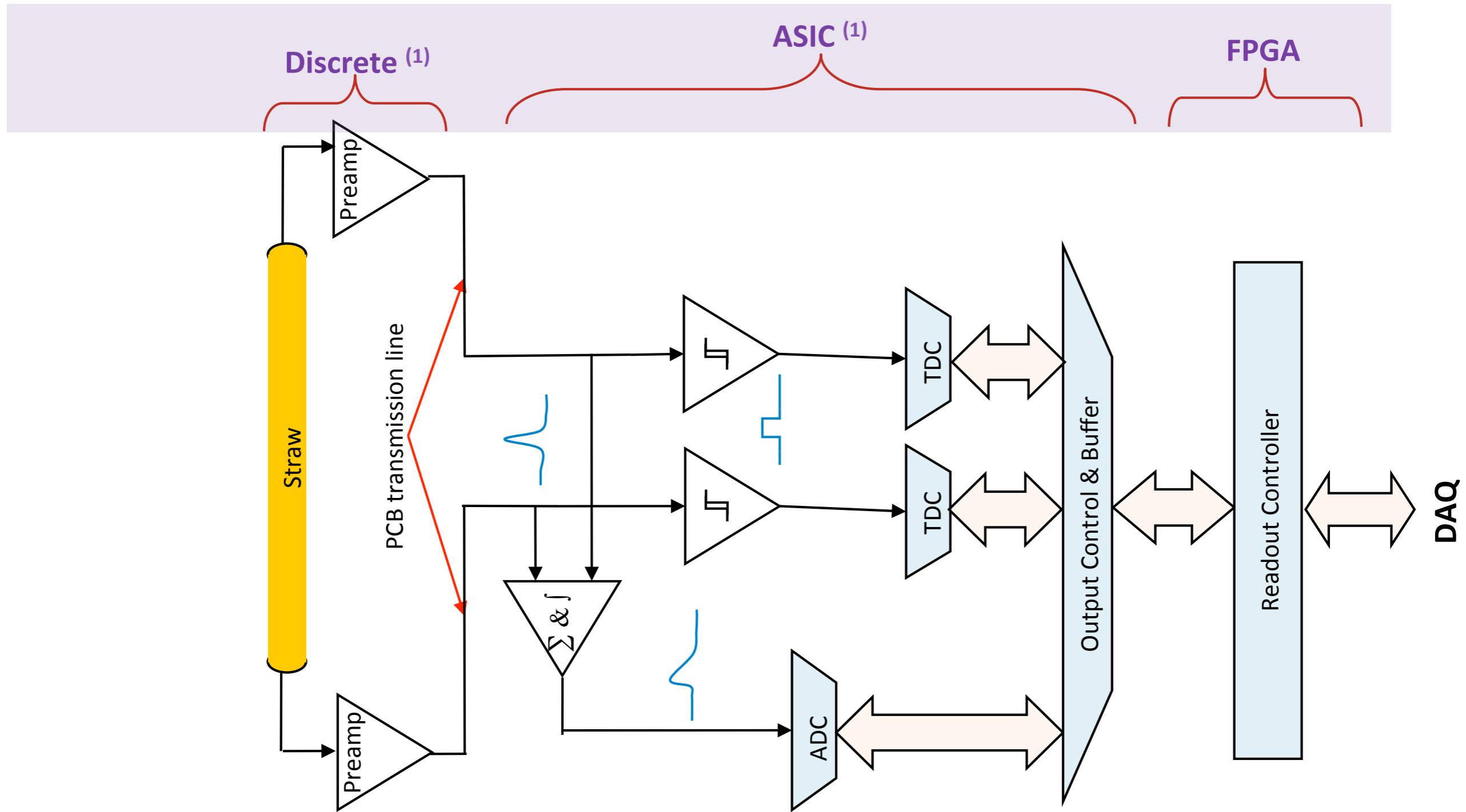
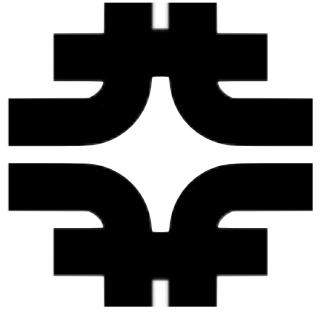


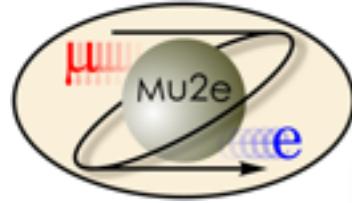
- Achieved 3.5cm with mu2e straws
  - ◆ Limited by noise → could improve (performance already to spec)



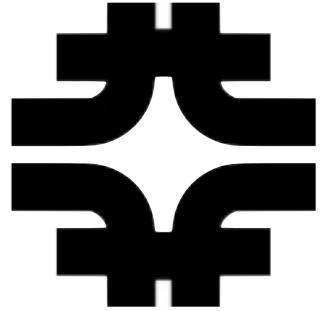


# Electronics

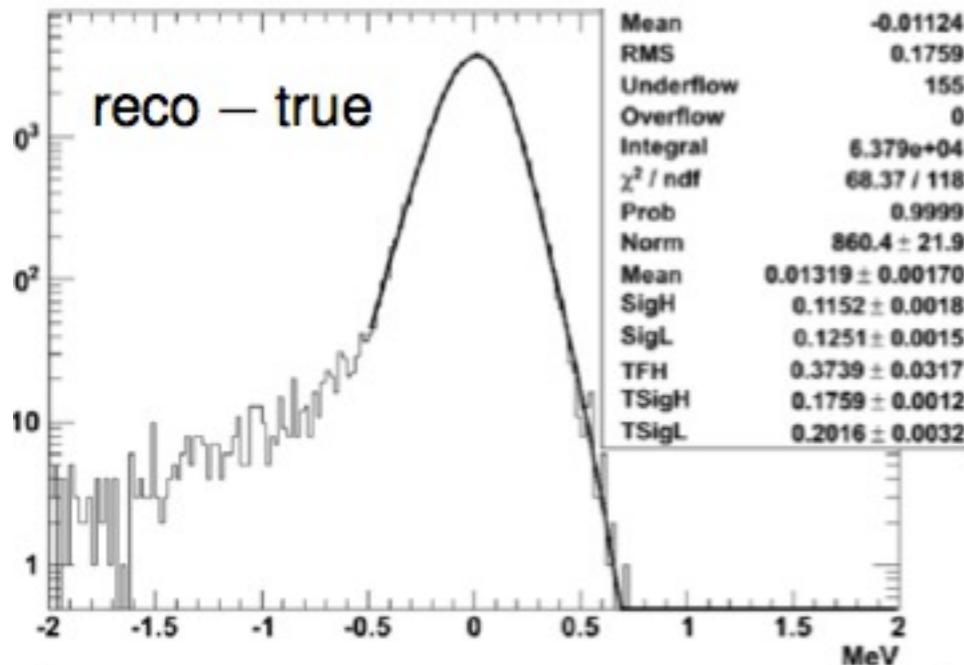




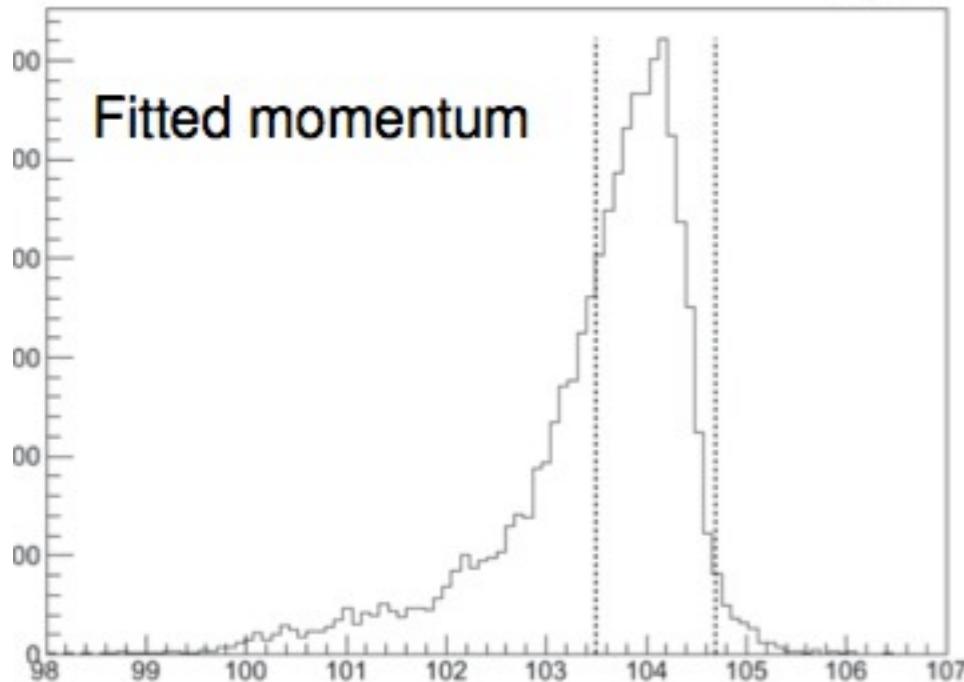
# Tracker performance

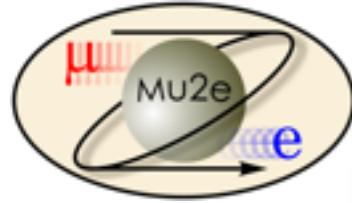


- Studied with full G4 simulations
- Realistic background rates included



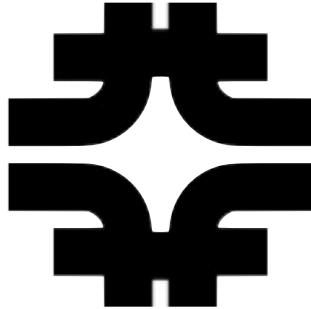
- Crystal ball function for intrinsic tracker resolution
  - Core  $\sigma=115\text{keV}/c$
  - Tail  $\sigma=176\text{keV}/c$
- Signal simulation
  - FWHM~1MeV/c
  - ~2/3 resolution = straggling before tracker
- Al foils
- Proton absorber



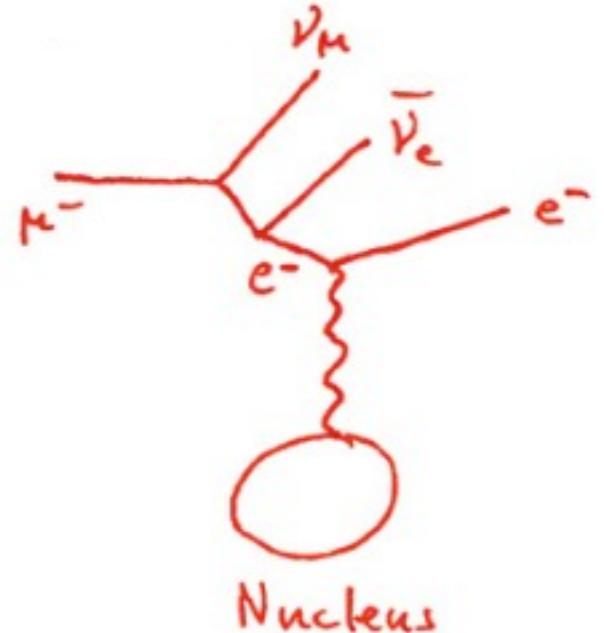


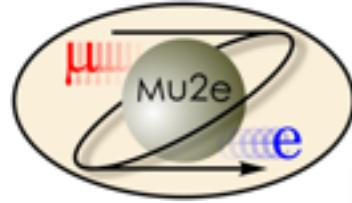
# DIO

## (why we need to know resolution)

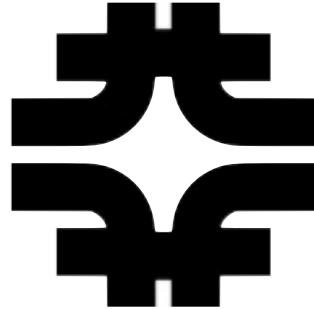


- ~100k events with  $P > 80\text{MeV}$
- well understood calculations (very important)
  - ◆ Czarnecki, Tormo, Marciano 2011 ([Phys. Rev. D 84, 013006 \(2011\)](#))
- $N_{\text{bkg}} = \text{Theory} \oplus \text{Resolution}$ 
  - ◆ add effect of changing reso here
- Special runs varying target foils, field, location of targets
- Monoenergetic line from  $\pi^+ \rightarrow e\nu$ 
  - ◆ ~70MeV  $e^+$
- New ideas being looked at
  - ◆ electrons from cosmic muons

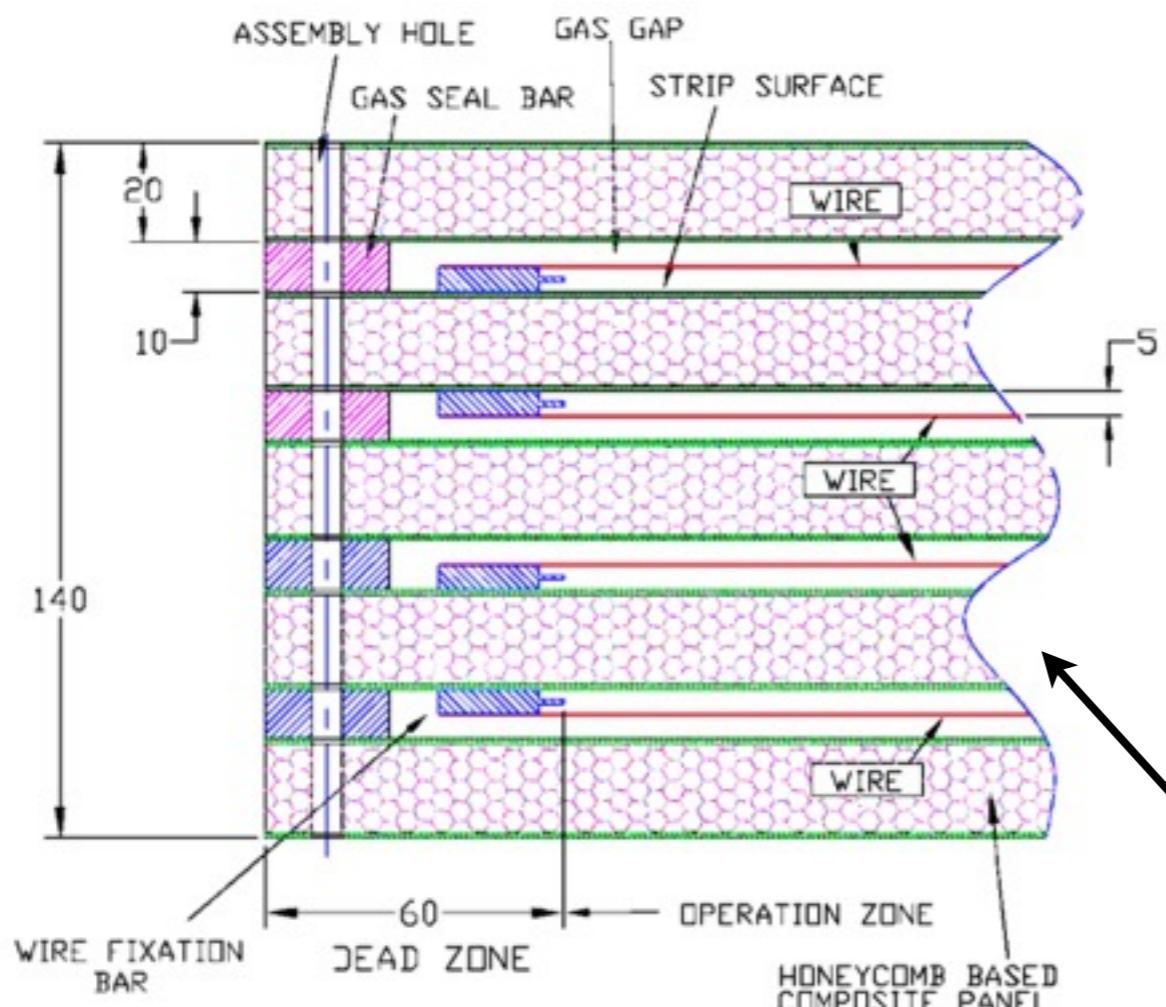




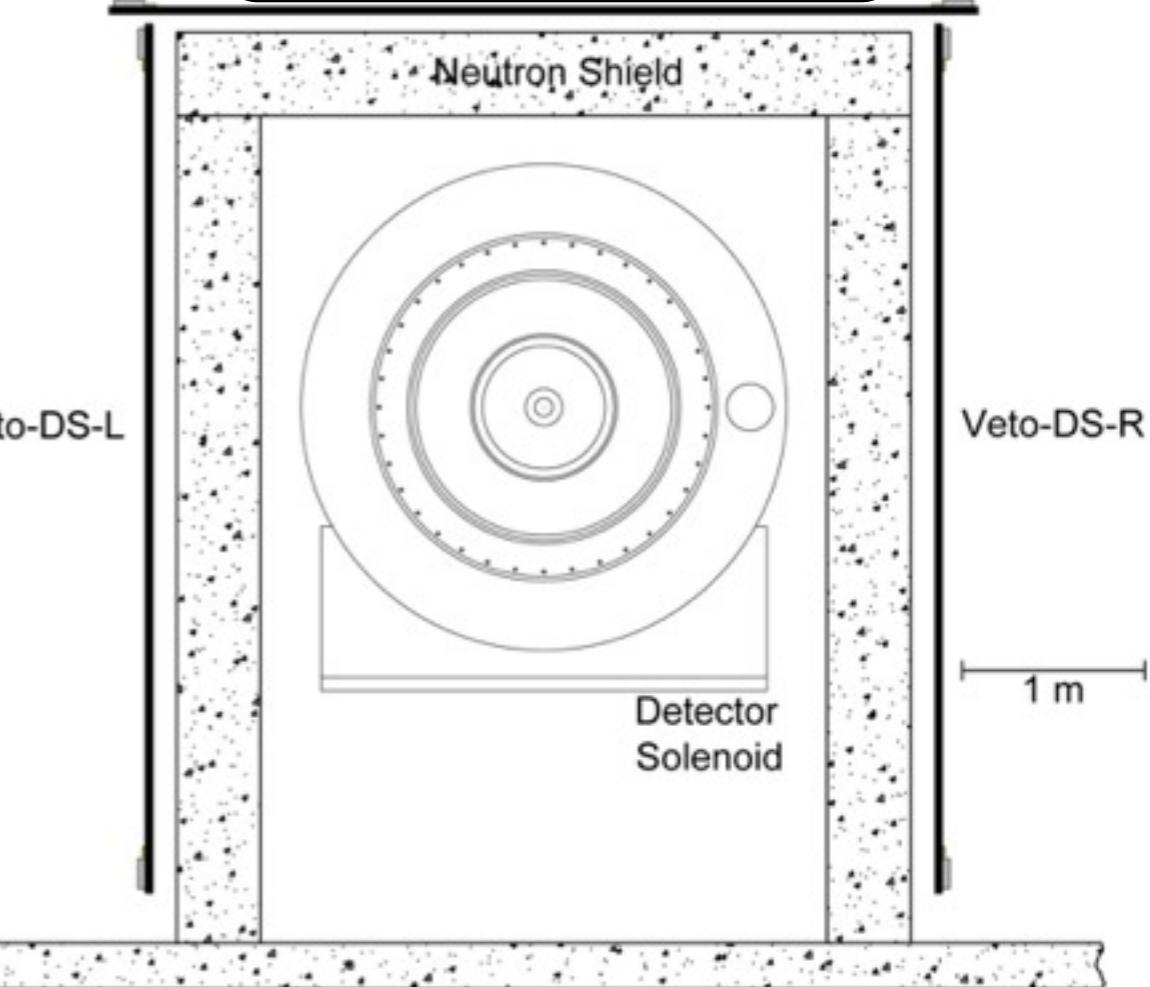
# Cosmic muons (why a cosmic veto)



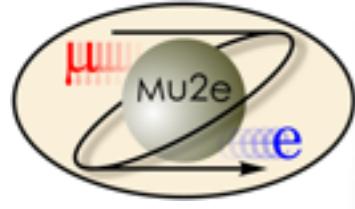
- The easiest way to make a 105MeV electron
- Hermetic around the detector
- 99.99% efficient
- <5ns time resolution
- resist neutron flux



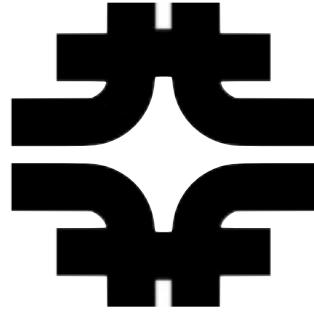
scintillating counters read by SiPMs  
(silicon photomultiplier)



- In some regions neutron flux too high
- Solution: cathode strip chambers → neutron blind



# Pions (why track positrons)



## ○ Radiative Pion Captures

- ◆  $\pi^- N \rightarrow \gamma N'$
- ◆  $\gamma N \rightarrow e^- e^+ N$

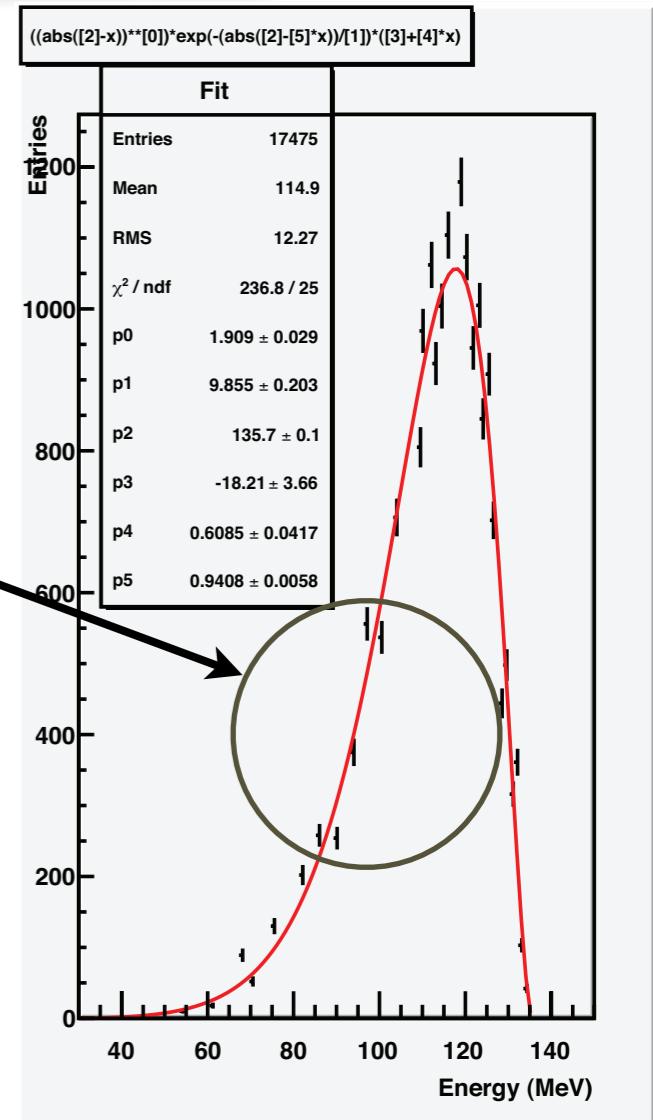
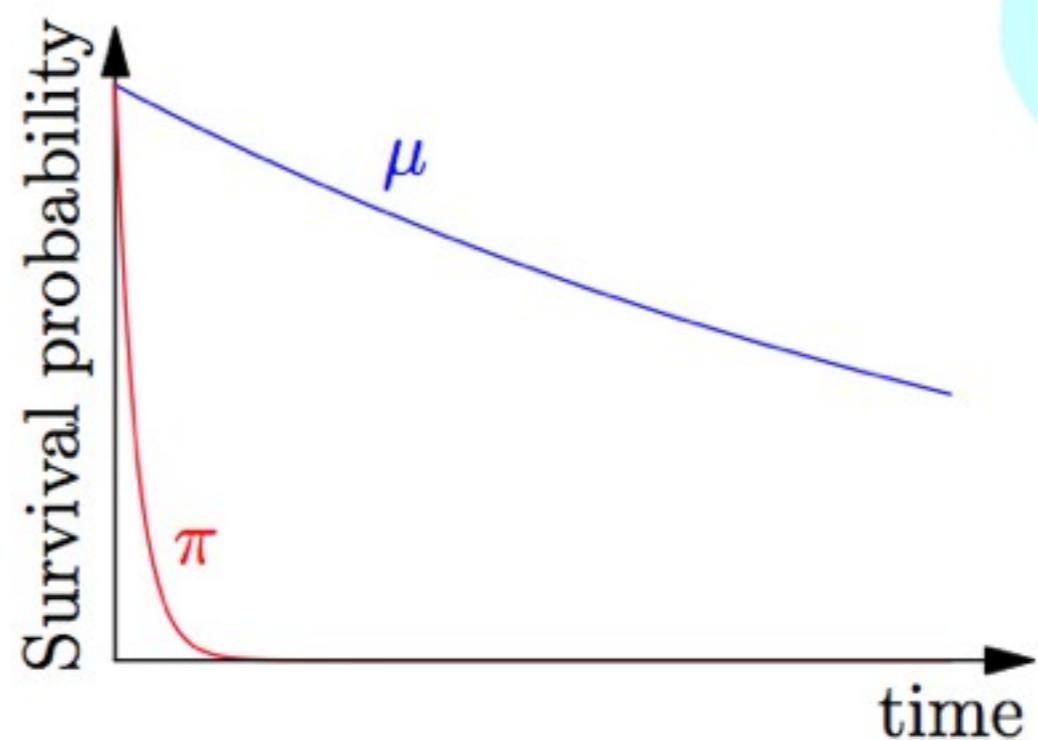
## ○ Fortunately, $\tau_\pi \ll \tau_\mu$

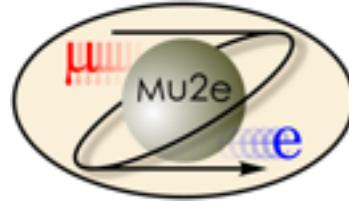
- ◆ waiting helps

## ○ $e^+ \approx e^-$

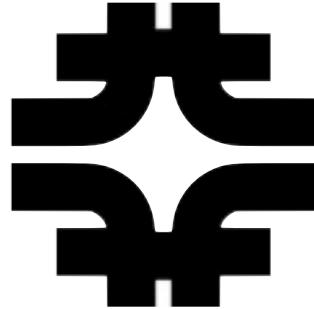
- ◆ measure  $e^+$  (use P sidebands for extrapolation)

$\gamma$  momentum can extend to  $m_\pi$  peak at ~110 MeV





# Late arriving particles (why $10^{-10}$ in between beam)



- Beam electrons,  $\mu$  and  $\pi$  decays in flight

- ◆ potential backgrounds

- Extinction between pulses  $< 10^{-10}$

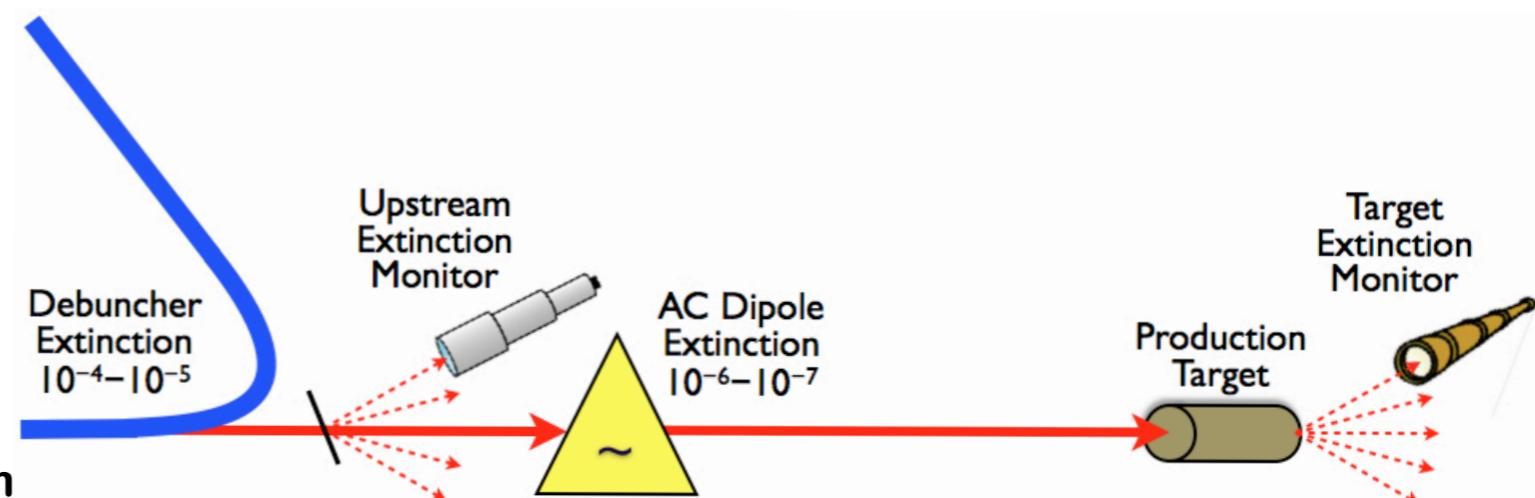
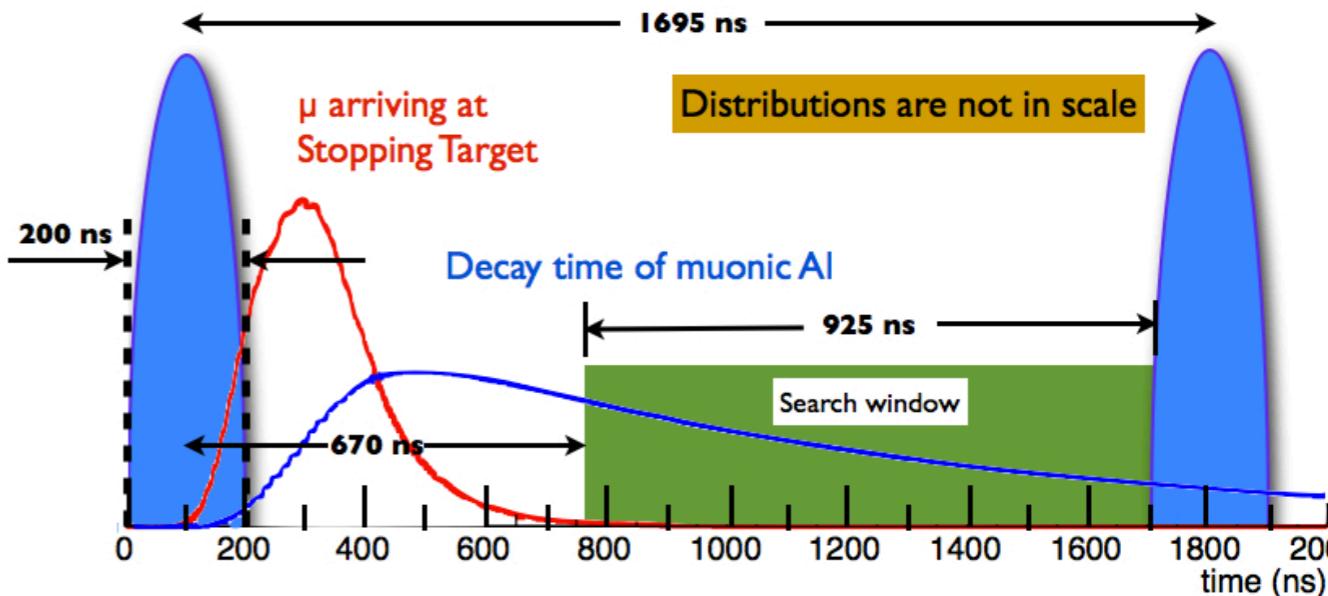
- ◆  $e = N_p \text{ out-of-pulse} / N_p \text{ in-pulse}$

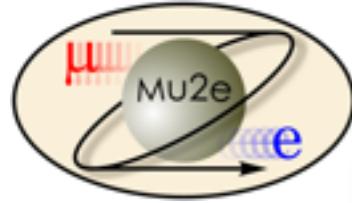
- ◆ requirement based on simulations

- AC dipole + collimators

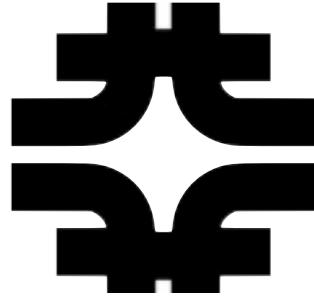
- We also need to measure this

- ◆ Fast response measurement upstream
  - ◆ Integrate (~1hours) for a statistical significant number of secondary tracks

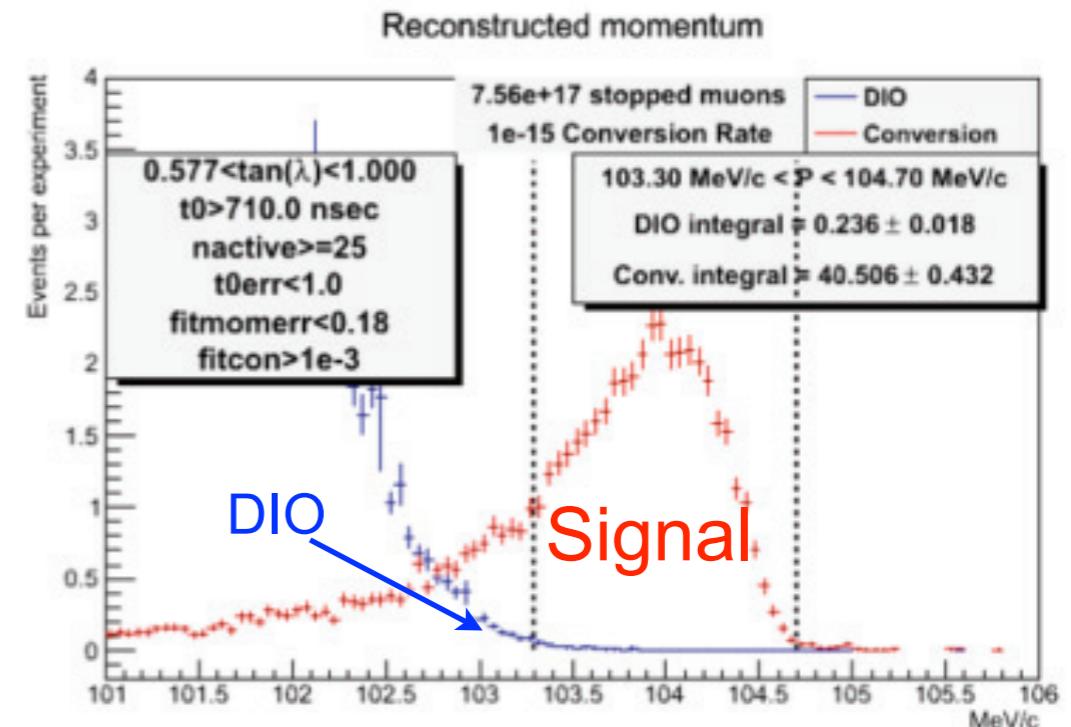




# Signal and Backgrounds

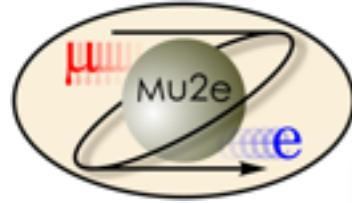


- 3 years of  $1.2 \times 10^{20}$  p/ year (8kW beam power)

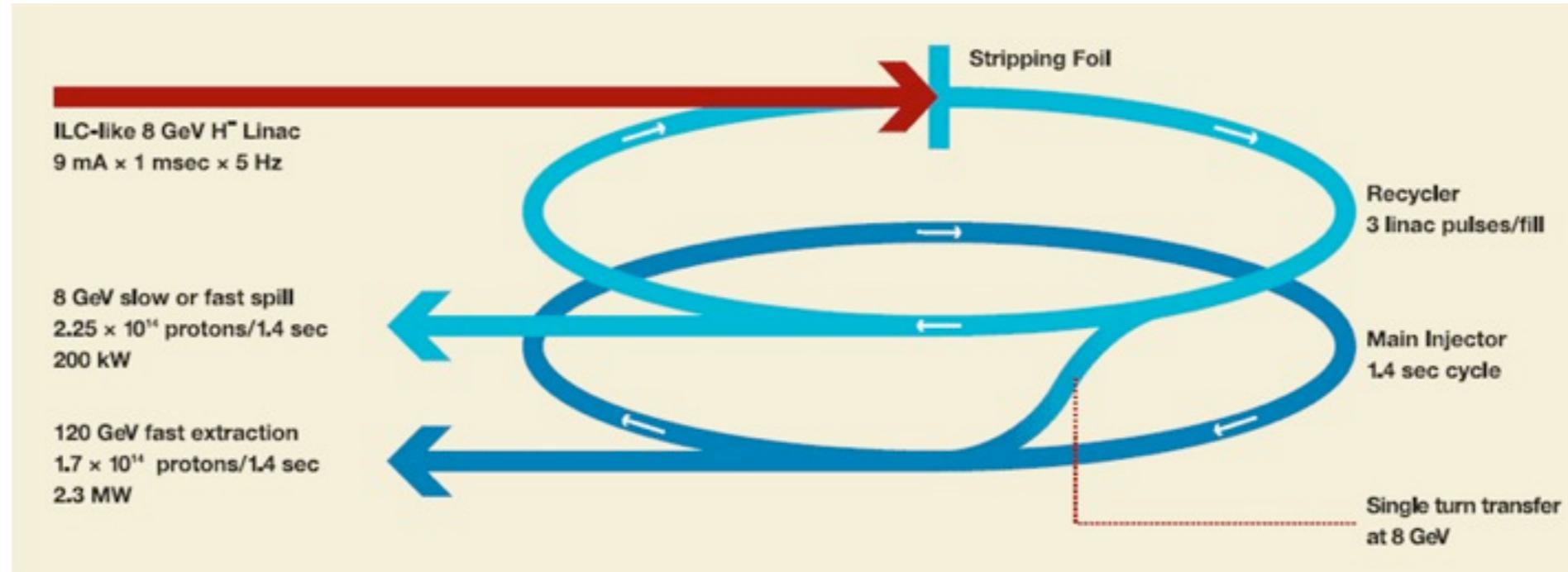
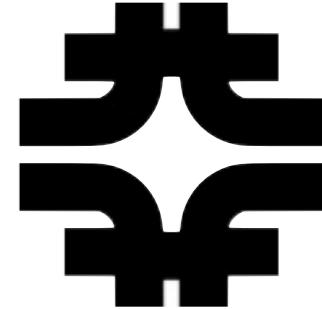


**For  $R_{\mu e} = 10^{-15}$  ~40 events**

Background	Size	Uncertainty	Source of Uncertainty
Muon Decay-In-Orbit	0.22	$\pm 0.06$	Acceptance and Energy Loss Modeling
Antiproton RPC	0.10	$\pm 0.05$	Cross-Section and Acceptance
Cosmic Rays	0.05	$\pm 0.05$	Statistics of Sample
Radiative Pion Capture	0.03	$\pm 0.007$	Acceptance and Reconstruction
Muon Decay-in-Flight	0.01	$\pm 0.003$	Cross-Section, Acceptance and Modeling
Pion Decay-in-Flight	0.003	$\pm 0.0015$	same
Beam Electrons	0.0006	$\pm 0.0003$	same
Radiative Muon Capture	$< 2 \times 10^{-6}$	—	Calculation
<b>Sum</b>	<b>0.41</b>	<b><math>\pm 0.08</math></b>	<b>Added in Quadrature</b>



# A look (far) ahead



- intense proton source that provides beam to
  - ◆ MI (neutrino program)
  - ◆ 8 GeV physics program
- Rich muon physics
  - ◆ mu2e
  - ◆  $\mu \rightarrow e \gamma$
  - ◆ muonium-antimuonium oscillations
  - ◆ others

mu2e signal?

YES

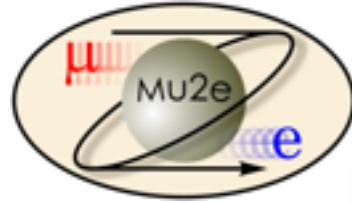
NO

Change target

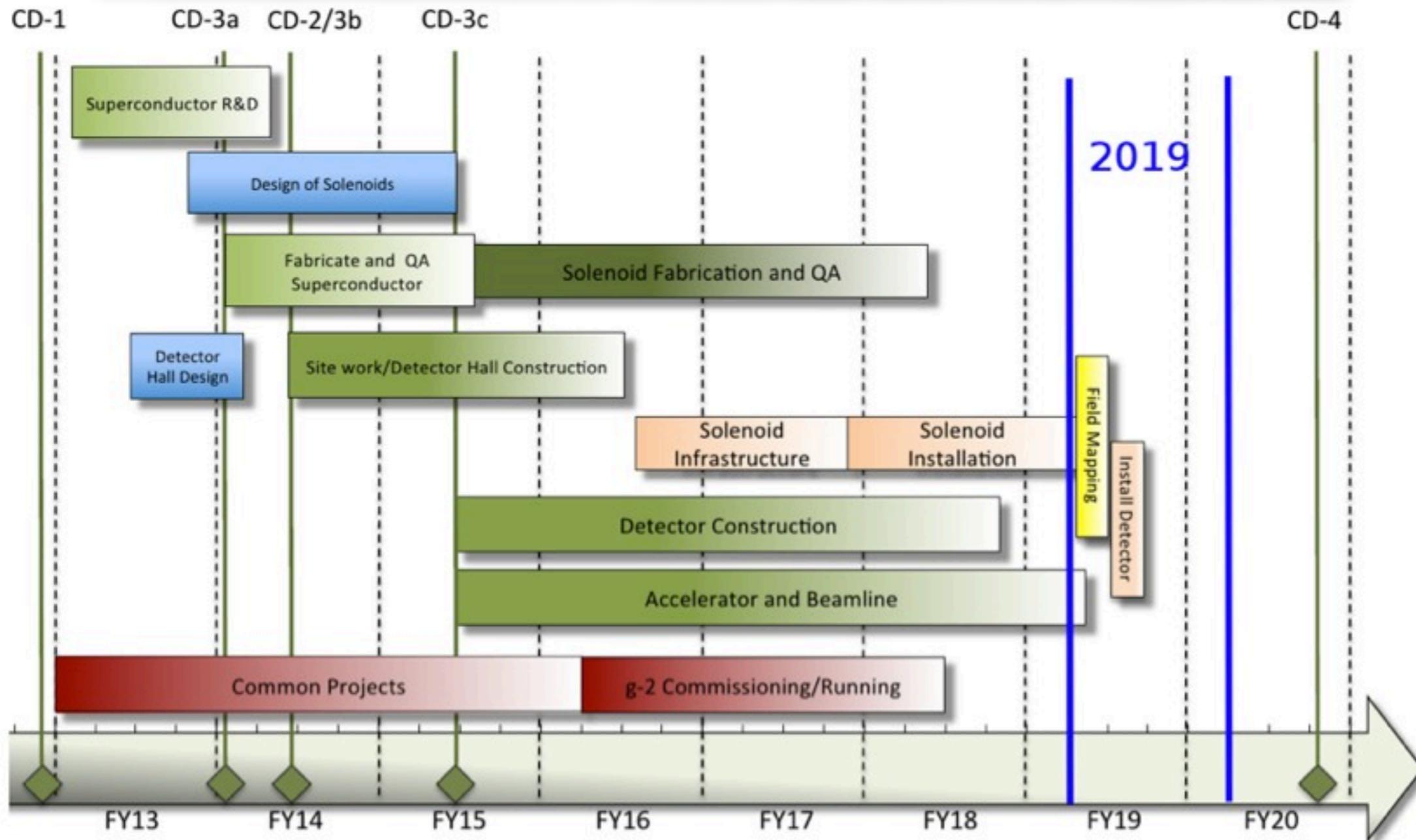
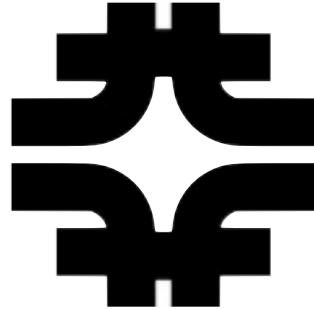
Repeat - higher sensitivity

Prompt backgrounds  
redesign muon beamline and detector

Higher rates, need to reduce backgrounds  
redesign muon beamline, detector, cosmic  
veto



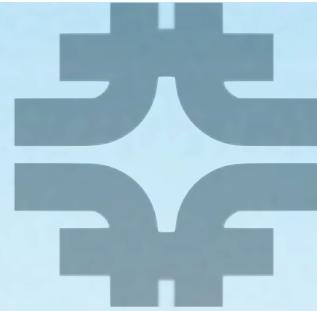
# mu2e schedule



- Solenoids drive the schedule
- Start detector construction in 2 years
- Expect to start cosmics run in 2019-2020



# Conclusions



- mu2e is a discovery experiment
  - ◆ 10000× more sensitive than last
- In the light of first LHC data it is even more important now to look for effects of new physics from scales >>LHC
- mu2e is capitalizing on a large existing infrastructure at Fermilab
- A very challenging experiment (where would be the fun if not) with very advanced understanding of the problems and how to address them

<http://mu2e.fnal.gov>